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Technology Evaluation Report

HYDROTECHNICS
IN SITU FLOW SENSOR

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, OH 45268

OFFICE OF
RESEARCH & DEVELOPMENT

NOTICE

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

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E. Timothy Oppelt, Director
National Risk Management Research Laboratory

ABSTRACT

The U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program evaluated performance of HydroTechnics, Inc. flow sensors in measuring the three-dimensional flow pattern created by operation of the Wasatch Environmental, Inc. (WEI) groundwater circulation well (GCW). The GCW is a dual-screened, in-well air-stripping system designed to remove volatile organic compounds (VOC) from groundwater. Operation of the GCW creates a groundwater flow pattern that forms a three-dimensional regime known as a “circulation cell.” EPA’s evaluation of the GCW circulation cell involved use of in situ groundwater velocity flow sensors that were developed at Sandia National Laboratories and manufactured by HydroTechnics, Inc.

This Technology Evaluation Report (TER) documents and summarizes the findings of EPA’s evaluation of HydroTechnics’ flow sensors. The flow sensors are in situ instruments that use a thermal perturbation technique to directly measure the velocity of groundwater flow in unconsolidated, saturated, porous media. The manufacturer claims that the flow meter can measure horizontal and vertical flow rates and direction in the range is 0.01 to 2.0 feet per day (ft/day) (0.3 to 60.96 centimeter per second [cm/s]).

The GCW is a patented system manufactured by WEI and was demonstrated at Cape Canaveral Air Station (CCAS) by the U.S. Air Force Center for Environmental Excellence (AFCEE). AFCEE conducted a comprehensive evaluation of the GCW, including contaminant mass removal rates, groundwater dye tracer studies, and numerical modeling. Demonstration data collected by AFCEE are documented separately in “Groundwater Circulation Well Technology Evaluation at Facility 1381, Cape Canaveral Air Station, Florida Technology Summary Report” (Parsons 2001).

The primary conclusions of EPA’s evaluation of the HydroTechnics flow sensors include:

- During GCW operation, the groundwater velocities measured by all seven sensors increased by more than 0.1 ft/day, indicating that (1) the sensors were within the circulation cell established by the GCW, and (2) the horizontal extent of groundwater circulation was greater than 15 feet. Flow direction data further support the establishment of a circulation cell and that all the flow sensors are within the horizontal extent of groundwater circulation cell.

- The demonstration data suggest that the flow sensors are responsive to changes in groundwater flow conditions and can be used to help define and evaluate the three-dimensional flow patterns.

This report is available from www.epa.go/ORD/SITE/reports.html. Printed copies can be obtained from National Service Center for Environmental Publications in Cincinnati, Ohio, at (800) 490-9198.

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AFCEE	Air Force Center for Environmental Excellence
bgs	Below ground surface
^oC	Degrees Celsius
CCAS	Cape Canaveral Air Station
cm/s	Centimeters per second
DC	Direct current
DCE	Dichloroethene
DFT	Dipole flow test
EPA	U. S. Environmental Protection Agency
ft/day	Feet per day
GCW	Groundwater circulation well
gpm	Gallons per minute
HP	Horsepower
KSC	John F. Kennedy Space Center
msl	Mean sea level
NAPL	Nonaqueous phase liquids
NRMRL	National Risk Management Research Laboratory
ORD	Office of Research and Development
OSWER	Office of Solid Waste and Emergency Response
Parsons	Parsons Engineering Science, Inc.
psi	Pounds per square inch
PVC	Polyvinyl chloride
QA	Quality assurance
QAPP	Quality Assurance Project Plan
QC	Quality control
RPD	Relative percent difference
SARA	Superfund Amendments and Reauthorization Act
SITE	Superfund Innovative Technology Evaluation
TCE	Trichloroethene
TEP	Technology Evaluation Plan
TER	Technology evaluation report
Tetra Tech	Tetra Tech EM Inc.
VOC	Volatile organic compound
WEI	Wasatch Environmental, Inc.
µg/L	Micrograms per liter

CONVERSION FACTORS

	To Convert From:	*To:*	*Multiply By:*
Length:	inch	centimeter	2.54
	foot	meter	0.305
	mile	kilometer	1.61
Area:	square foot	square meter	0.0929
	acre	square meter	4,047
Volume:	gallon	liter	3.78
	cubic foot	cubic meter	0.0283
	cubic foot	gallon	7.48
	cubic foot	cubic centimeter	28,317
Mass:	pound	kilogram	0.454
Temperature:	(EFahrenheit - 32)	ECelsius	0.556
Time	days	minutes	1440

ACKNOWLEDGEMENTS

This report was prepared for the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program by Tetra Tech EM Inc. under the direction and coordination of Ms. Michelle Simon, work assignment manager in the Land Remediation and Pollution Control Division of the National Risk Management Research Laboratory in Cincinnati, Ohio.

The groundwater circulation well demonstration was a cooperative effort that involved the following personnel from the EPA Site Program and the U.S. Air Force Center for Environmental Excellence (AFCEE)

Ms. Annette Gatchett	EPA, NRMRL, LRPCD, Assistant Director for Technology
Ms. Michelle Simon	EPA, LRPCD, SITE Work Assignment Manager
Ms. Ann Vega	EPA, LRPCD, Quality Assurance Officer
Mr. James Gonzales	AFCEE, Project Manager
Mr. John Hicks	Parsons Engineering, Project Manager
Ms. Martha Moses	HydroTechnics, Owner
Dr. Robert Knowlton	HydroTechnics, Project Manager
Mr. Tabor Dehart	Wasatch Environmental Inc., Project Manager
Dr. Rick Johnson	Oregon Graduate Research, Consultant
Dr. Robert Hinchee	Battelle Corporation, Consultant
Roger Argus	Tetra Tech EM Inc., EPA Contractor
Ben Hough	Tetra Tech EM Inc., EPA Contractor
Tong Li	Tetra Tech EM Inc., EPA Contractor

EXECUTIVE SUMMARY

The U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program evaluated performance of HydroTechnics, Inc. flow sensors in measuring the three-dimensional flow pattern created by operation of the Wasatch Environmental, Inc. (WEI) groundwater circulation well (GCW). The GCW is a dual-screened, in-well air-stripping system designed to remove volatile organic compounds (VOC) from groundwater. Operation of the GCW creates a groundwater flow pattern that forms a three-dimensional regime known as a "circulation cell." EPA's evaluation of the GCW circulation cell involved use of in situ groundwater velocity flow sensors that were developed at Sandia National Laboratories and manufactured by HydroTechnics, Inc.

The HydroTechnics flow sensors are in situ instruments that use a thermal perturbation technique to directly measure the velocity of groundwater flow in unconsolidated, saturated, porous media. The flow sensors differ from other devices that measure groundwater velocity in that they are in direct contact with the unconsolidated aquifer matrix where the flow is to be measured, thereby avoiding borehole effects. The flow sensor is a thin, cylindrical device that is permanently buried at the depth where the velocity of groundwater flow is to be measured. The manufacturer claims that the flow meter can measure groundwater flow in the range is 0.01 to 2.0 feet per day (ft/day) (0.3 to 60.96 centimeter per second [cm/s]) with an error of +/- 0.001 feet (0.03 centimeter). Data collected from the flow sensors include the horizontal and vertical groundwater flow rate as well as groundwater flow direction.

The GCW is a patented system manufactured by WEI and was demonstrated at Cape Canaveral Air Station (CCAS) by the U.S. Air Force Center for Environmental Excellence (AFCEE). AFCEE conducted a comprehensive evaluation of the GCW, including contaminant mass removal rates, groundwater dye tracer studies, and numerical modeling. The results of the AFCEE study can be found in the report entitled "Groundwater Circulation Well Technology Evaluation at Facility 1381, Cape Canaveral Air Station, Florida – Final Report" (Parsons, 2001). The results of the EPA SITE Program demonstration provided additional hydraulic data that are useful in characterizing the GCW circulation cell.

AFCEE managed the overall GCW technology evaluation and was responsible for installation, operation, and optimization of the GCW. EPA was responsible for aquifer hydraulic testing and the installation and

acquisition of data from the HydroTechnics flow sensors. Additionally, the Oregon Graduate Institute conducted dye tracer studies and modeling to evaluate the GCW circulation cell.

EPA's evaluation of the HydroTechnics flow sensors was designed with one primary and four secondary objectives to assess the sensor's ability to detect the groundwater circulation cell established by the GCW. The primary and secondary objectives were evaluated by collecting and interpreting data from seven flow sensors, conducting a series of aquifer hydraulic tests, and collecting GCW operational data during four modes of operation. The four modes of operation include: (1) natural flow conditions, (2) circulation conditions, (3) pump-and-treat testing, and (4) aquifer hydraulic testing (step-drawdown, constant-rate pump testing, and dipole flow testing). Data were collected and analyzed using the methods and procedures presented in the Technology Evaluation Plan/Quality Assurance Project Plan (TEP/QAPP) for the project (Tetra Tech 2000). The data from the groundwater flow sensors yielded valuable information regarding the circulation cell of the GCW. The conclusions of the technology evaluation, as they relate to the demonstration project objectives, include:

Primary Conclusions

P1 Evaluate the flow sensor's ability to detect the horizontal extent of the GCW groundwater circulation cell based on a change in the groundwater velocity criterion of 0.1 foot per day (0.03 meter per day)

- During the GCW circulation operation mode, the groundwater velocities measured by all seven sensors increased by more than 0.1 ft/day, indicating that (1) the sensors were within the circulation cell established by the GCW, and (2) the horizontal extent of groundwater circulation was greater than 15 feet. Furthermore, the groundwater flow direction data suggest that groundwater in the upper portion of the treatment zone generally flows radially away from the GCW and that groundwater in the bottom of the treatment zone generally flows radially towards the GCW. This flow direction data further support the establishment of a circulation cell and that all the flow sensors are within the horizontal extent of groundwater circulation cell.

- The data from the four modes of GCW operation suggest that the flow sensors are responsive to changes in groundwater flow conditions and can be used to help define and evaluate the three-dimensional flow pattern created by the GCW. The immediate response of the sensors to changes in GCW operation suggest that the groundwater circulation cell is established within hours instead of days. Additionally, the velocity data from the flow sensors suggest that the GCW circulation flow was generally constant during operation in the circulation mode.

Secondary Conclusions

S1 Evaluate the reproducibility of the groundwater velocity sensor data

- The reproducibility of the sensors during steady state conditions ranged from 0.1 to 23 percent with an average of 1.9 percent and a standard deviation of 3.8 percent.

S2 Evaluate the three-dimensional groundwater flow surrounding the GCW

- Groundwater flow patterns, as measured by the flow sensors, were documented for each of the four GCW operational modes and are depicted graphically to illustrate general flow patterns in the vicinity of the GCW during each mode of operation.

S3 Document the operating parameters of the GCW

- GCW pumping rate, duration of system operation, and GCW shutdowns were documented for each of the four modes of operation:

GCW Operational Mode	Pumping Rate	Duration of Operation	GCW Shutdowns
Circulation	4 gpm	July 10 – 28, 2000	1 shutdown for mechanical maintenance
Pump and Treat	4 gpm	August 2 – 29, 2000	7 shutdowns for mechanical repairs
Aquifer Hydraulic Testing	Various	September 13 – 19, 2000	None
Natural Conditions	No pumping	GCW not operated	GCW not operated

S4 Document the hydrogeologic characteristics at the demonstration site

- Natural groundwater flow velocities at the CCAS Facility 1381 site are very low, ranging from 0.03 to 0.21 ft/day (0.009 to 0.064 meter/day).

- The conductivity of the aquifer at the Facility 1381 site decreased with depth. Based on aquifer hydraulic test data, the hydraulic conductivity ranges from 43 to 53 ft/day (1.5×10^{-4} to 1.9×10^{-4} cm/s) for the shallow zone (upper 7 feet or 2.1 meters) and 5 to 10 ft/day (1.8×10^{-5} to 3.5×10^{-5} cm/s) for the deeper zone (7 to 25 feet deep or 2.1 to 7.6 meters). The Storativity of the lower aquifer zone ranges from 0.006 to 0.007 and specific yield ranges from 0.06 to 0.09. The average anisotropic ratio (that is, the ratio of horizontal to vertical hydraulic conductivity) is 2.4, based on steady-state dipole flow test interpretation.

Additional findings and observations based on the EPA demonstration of the flow sensors include:

- According to the developer, the flow sensors measure flow in a 3.3 cubic feet [1 cubic meter] area volume immediately surrounding the sensor,) and are subject to local heterogeneities. Complex site hydrogeological conditions may require a large number of flow sensors to adequately define the circulation cell and characterize flow patterns.

- To more fully evaluate the three-dimensional flow surrounding this GCW, additional sensors should have been installed at varying distances and depths from the GCW. Flow sensors should be installed at upgradient, downgradient, and cross-gradient locations at a minimum of three different distances from the GCW. The flow sensors also should be installed at three different depths corresponding to shallow and deep GCW screens as well as in the middle portion of the monitored zone between the two screens. The shallow sensors should be installed a minimum of 5 feet (1.5 meters) below the water table, which would minimize the impact of temperature variations caused by the vadose zone. Only seven sensors were installed for this project because preliminary modeling indicated that the circulation cell would be smaller than what was actually observed in both the upgradient and cross gradient directions.

- HydroTechnics recommends installing the flow sensors with five feet (1.5 meters) of submergence because the shallow portion of the groundwater will heat up during the day, creating a thermal gradient that the sensor measures as water flow. For the EPA demonstration, the shallow sensors were installed with less than 5 feet of submergence because preliminary modeling indicated that there would not be significant flow deeper than 3 feet (1 meter) into the formation. Data from the shallow sensors were successfully corrected by subtracting the background temperature gradient.

- HydroTechnics recommends allowing at minimum of 7 days for the sensors to come to thermal equilibrium. During the EPA demonstration, short-term aquifer tests resulted in large but short-term changes in groundwater flow, that were successfully measured by the flow sensors.

- The cost of a single flow sensor was $2,500. The total cost for the seven sensors, sensor data analysis for a period of 1 year, and installation was $70,000 for this project. Costs at other sites may vary depending on installation depth and subsurface conditions.

1.0 INTRODUCTION

This Technology Evaluation Report (TER) documents and summarizes the findings of an evaluation of HydroTechnics, Inc. in situ flow sensors in measuring the groundwater flow patterns created by an innovative groundwater circulating well (GCW) installed at Facility 1381 at the U.S. Air Force 45th Space Wing, Cape Canaveral Air Station (CCAS), Florida (Figures 1 and 2). The U.S. Environmental Protection Agency (EPA) National Risk Management Research Laboratory (NRMRL) evaluated the using in situ groundwater flow sensors under the Superfund Innovative Technology Evaluation (SITE) Program. The EPA's evaluation was a component of a comprehensive evaluation of the GCW conducted by the U.S. Air Force Center for Environmental Excellence (AFCEE). The flow sensors were evaluated for the SITE Program by measuring the magnitude and direction of groundwater flow near the GCW and by conducting aquifer hydraulic tests using the GCW.

The GCW selected is a patented system manufactured by Wasatch Environmental, Inc. (WEI). AFCEE's support contractor, Parsons Engineering, managed the overall technology evaluation and was responsible for installation, operation, and optimization of the GCW. The EPA SITE Program managed installation and acquisition of data from in situ groundwater velocity sensors and the aquifer hydraulic testing.

This report documents the activities conducted during the demonstration and summarizes data collected by EPA. Demonstration data collected by AFCEE are documented separately and are not included in this report.

The TER is divided into eight sections. Section 1.0 presents the project background, information on the SITE Program, a description of the technology, and key contacts. Section 2.0 describes the environmental setting of the demonstration site and the objectives of the evaluation, methods and procedures, and modifications to the Technology Evaluation Plan/Quality Assurance Project Plan (TEP/QAPP) (Tetra Tech 2000). Section 3.0 describes the groundwater circulation system, and Section 4.0 describes the groundwater flow sensors. Section 5.0 presents interpretation of data from the groundwater flow sensors used during the evaluation. Section 6.0 presents the results of the technology evaluation, while Section 7.0 presents the conclusions of the evaluation. References are included in Section 8.0.

1.1 PROJECT BACKGROUND

As part of ongoing efforts to address impacts to groundwater from chlorinated solvents, CCAS is conducting a series of pilot-scale treatability studies to obtain site-specific data on performance and cost for potentially applicable remediation technologies. AFCEE identified the WEI GCW as a possible solution for remediation of nonaqueous-phase liquids (NAPL) source areas such as Facility 1381. Facility 1381 was selected as the demonstration site because it was thought to have a favorable site hydrogeologic condition (relatively high hydraulic conductivity) and the presence of a NAPL source.

GCW technologies have been proposed as a cost-effective alternative to traditional pump-and-treat technologies for remediation of groundwater contaminated with volatile organic compounds (VOC). AFCEE developed a comprehensive test plan to evaluate the GCW, which included installation of a 6-inch GCW and 99 microwells that radiate from the GCW; collection of samples from the soil core, groundwater, and air for subsequent geotechnical and chemical analysis; completion of a dye tracer test; and development of a site groundwater flow model. AFCEE alternated operation of the GCW between pump-and-treat mode and circulation mode to obtain reliable data on the relative capabilities of the GCW technology. Samples of groundwater and air were collected during both modes of operation to obtain performance data under various operating scenarios and to allow comparisons of results.

AFCEE invited EPA to participate in an evaluation of a GCW at CCAS Facility 1381. To evaluate the circulation cell, EPA installed in situ groundwater flow sensors to measure the magnitude and direction of groundwater flow near the GCW, and conducted a series of aquifer hydraulic tests. Data from the groundwater flow sensors were collected during (1) long-term pump-and-treat operation, (2) long-term GCW operation, (3) final pump-and-treat operation, (4) aquifer hydraulic tests, and (5) post-GCW operation.

A summary of the various operational periods is provided below.

Long-Term Pump-and-Treat Operation. The GCW was installed at the site in November 1999. After a tidal influence study, tracer test, and a series of short-term aquifer hydraulic tests, the system began operation in pump-and-treat mode in February 2000. The system remained in pump-and-treat mode through April 2000. AFCEE monitored the system to calculate mass removal rates for comparison to rates achieved during other modes of operation by the GCW.

Long-Term GCW Operation. Long-term operation of the GCW was initiated in April and continued until July 2000. The in situ groundwater flow sensors were installed in June 2000. Continuous collection of data on groundwater flow from the sensors was initiated in July 2000.

Final Pump-and-Treat Operation. Final pump-and-treat operation of the GCW was conducted during August 2000. Eight transducers were installed to evaluate changes in hydraulic head in the aquifer during August 2000.

Aquifer Hydraulic Test Operation. A series of aquifer hydraulic tests were conducted in September 2000. Hydraulic head data were collected from the aquifer using eight pressure transducers, and data on direction and magnitude of groundwater flow were collected from the seven in situ groundwater flow sensors.

Post-GCW Operation. The GCW has not operated after aquifer hydraulic testing was completed in September 2001. EPA collected data from the in situ groundwater flow sensors from September 2000 through September 2001 to document groundwater flow during non-operation of the GCW.

1.2 DESCRIPTION OF FLOW SENSOR AND GCW TECHNOLOGIES

The groundwater flow sensors installed at CCAS were developed at Sandia National Laboratories and manufactured by HydroTechnics, both of Albuquerque, New Mexico. The flow sensors are in situ instruments that use a thermal perturbation technique to directly measure the velocity of groundwater flow in unconsolidated, saturated, porous media. The flow sensors differ from other devices to measure groundwater velocity in that they are in direct contact with the unconsolidated aquifer matrix where the flow is to be measured, thereby avoiding borehole effects. The flow sensor is a thin, cylindrical device that is permanently buried at the depth where the velocity of groundwater flow is to be measured.

The WEI GCW is an in situ groundwater remediation system designed to circulate groundwater in the aquifer and strip VOCs. In the WEI system, airlift pumping lifts groundwater from a screen in the lower section of the well. Air is pumped to the bottom of the well by a blower, reducing the weight of the water column. Groundwater and air are then lifted to an upper screen, where the air strips VOCs and the groundwater is allowed to discharge back into the aquifer. The air stream used to strip VOCs is extracted from the wellhead and is treated before it is released to the atmosphere. Groundwater that reenters the aquifer through the top screen flows vertically downward and can be recaptured by the GCW, so that it can be treated again. The three-dimensional groundwater flow regime developed by the GCW is termed a "circulation cell," and its characteristics are critical to the effectiveness of the technology. Key parameters of the circulation cell are its size, or radius, and its percent capture (Parsons 1999a).

1.3 THE SUPERFUND INNOVATIVE TECHNOLOGY EVALUATION PROGRAM

EPA's Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) created the SITE Program in response to the Superfund Amendments and Reauthorization Act of 1986 (SARA). The SITE Program promotes the development, evaluation, and use of new or innovative technologies to clean up Superfund sites across the country.

The primary purpose of the SITE Program is to maximize the use of alternatives in cleaning up hazardous waste sites by encouraging development and evaluation of innovative treatment and monitoring technologies. It consists of three major elements:

- The Technology Evaluation Program
- The Monitoring and Measurement Technologies Program
- The Technology Transfer Program

The objective of the Technology Evaluation Program is to develop reliable data on performance and cost for innovative technologies so that potential users may assess the technology's site-specific applicability. Technologies evaluated are either currently available or are close to being available for remediation of Superfund sites. SITE evaluations are conducted on hazardous waste sites under circumstances that closely simulate full-scale remediation conditions, thus ensuring the usefulness and reliability of the information collected.

Existing technologies that improve field monitoring and site characterizations are identified in the Monitoring and Measurement Technologies Program. This program supports new technologies that provide faster, more cost-effective contamination and site assessment data. The Monitoring and Measurement Technologies Program also formulates protocols and standard operating procedures for evaluation methods and equipment.

The Technology Transfer Program disseminates technical information on innovative technologies in the Evaluation and Monitoring and Measurements Technologies Programs through various activities. These activities increase the awareness and promote the use of innovative technologies for assessment and remediation at Superfund sites. The goal of the technology transfer is to develop communication among individuals who require up-to-date technical information.

1.4 KEY CONTACTS

Additional information on the SITE Program and the evaluation can be obtained from the EPA Project Manager:

Michelle Simon
U.S. Environmental Protection Agency
Office of Research and Development
26 West Martin Luther King Drive
Cincinnati, Ohio 45268
Telephone: (513) 569-7469, Facsimile: (513) 569-7676
E-mail: simon.michelle@epa.gov

Additional information on AFCEE's evaluation of the GCW technology can be obtained from the AFCEE project manager:

James Gonzales
Air Force Center for Environmental Excellence
3207 North Road
Brooks AFB, Texas 78235-5363
Telephone: (210) 536-4324, Facsimile: (210) 536-4330
E-mail: james.gonzales@hqafcee.brooks.af.mil

Additional information on the WEI GCW technology or the evaluation can be obtained from the technology vendor:

Tabor DeHart
Wasatch Environmental, Inc.
2410 West California Avenue
Salt Lake City, Utah 84104
Telephone: (801) 972-8400, Facsimile: (801) 972-8459
E-mail: wasatchenv@aol.com

Additional information on in situ flow sensors or this evaluation can be obtained from:

Martha Moses
HydroTechnics
P.O. Box 92828
Albuquerque, NM 87199-2828
Telephone: (505) 797-2421, Facsimile: (505) 797-0838
E-Mail: info@hydrotechnics.com

In addition, information on the SITE Program is available through the following on-line information clearinghouses:

- SITE Program Home Page: http://www.epa.gov/ORD/SITE. All recent SITE reports, including this one can be downloaded from this web site.

- The Alternative Treatment Technology Information Center (ATTIC) Internet Access: http://www.epa.gov/attic

- Cleanup Information Bulletin Board System (CLU-IN)
  Help Desk: (301) 589-8368; Internet Access: http://www.clu-in.org

- EPA Remediation and Characterization Innovative Technologies
  Internet Access: http://www.epa.reachit.org

- Groundwater Remediation Technology Center
  Internet Access: http://www.gwrtac.org

Technical reports may be obtained by contacting the National Service Center for Environmental Publications in Cincinnati, Ohio. To find out about newly published documents or to be included on the SITE mailing list, call or write to:

U.S. EPA/NSCEP
P.O. Box 42419
Cincinnati, Ohio 45242-2419
(800) 490-9198

2.0 SITE DESCRIPTION, OBJECTIVES, AND PROCEDURES

A description of the demonstration site, as well as objectives and procedures for the flow sensor evaluation, are described in the following sections. Specifically, Section 2.1 provides a demonstration site description; Section 2.2 describes the objectives of the evaluation; Section 2.3 describes the field and analytical methods including placement and installation of groundwater velocity sensors, design of the evaluation, data presentation, and data analysis; Section 2.4 presents the quality assurance and quality control (QA/QC) procedures; and Section 2.5 presents the modifications to the Technology Evaluation Plan that were implemented during the technology evaluation.

2.1 DEMONSTRATION SITE DESCRIPTION

This section provides information on site conditions, including the site location, history, geology, hydrogeology, and soil and groundwater contamination at CCAS Facility 1381. This section also provides a summary of the site hydrogeological conceptual model.

2.1.1 Site Location

CCAS is on Canaveral Peninsula, which is the easternmost portion of Merritt Island, a barrier island in Brevard County on the Atlantic coast of Florida (Figure 1). The main complex of CCAS consists of assembly and launch facilities for missiles and space vehicles and occupies 25 square miles. The property is bounded by the Atlantic Ocean to the east and the Banana River to the west. The southern boundary is an artificial shipping canal; the John F. Kennedy Space Center (KSC) adjoins CCAS to the north. Facility 1381 is located in the east-central portion of CCAS. A site map is included as Figure 2.

2.1.2 Site History

Since it was established in 1950, CCAS has been a proving ground for research, development, and testing of the country's military missile programs. Seventy-three miles of paved roads at CCAS connect the various launch and support facilities with the centralized industrial area. The primary industrial activities at CCAS support missile launches from CCAS and spacecraft launches from KSC. CCAS also provides support for submarine port activities (Parsons 1999b).

Facility 1381 has been used for several operations since it was built in 1958. For the 10 years after construction, Facility 1381 was used as the Guidance Azimuth Transfer Building. Aerial photographs from that time indicate numerous drums and tanker trucks at the facility. Verbal reports indicate that the tanker trucks were used for dumping waste solvents in the forest that surrounds the facility. In 1968, the site became the In-Place Precision Cleaning Laboratory. Specific activities included cleaning metal components in acid and solvent dip tanks, resulting in the generation of approximately 3,300 gallons of waste trichloroethene (TCE) per year. In 1977, the facility became known as the Ordnance Support Facility, and its name has remained unchanged to the present time (Parsons 1999b).

2.1.3 Regional and Site Geology

This section discusses the regional and site geology near CCAS and Facility 1381.

2.1.3.1 Regional Geology

Florida constitutes the southeast portion of the Atlantic Coastal Plain physiographic province of the southeastern United States. The Coastal Plain is a thick sequence of unconsolidated to semiconsolidated sedimentary rocks that range from Jurassic to Holocene in age. The configuration of rocks in the Coastal Plain is a tilted wedge that slopes and thickens seaward toward the Atlantic Ocean and the Gulf of Mexico.

In Florida, the sequence of sedimentary rocks that make up the Coastal Plain is referred to as the Florida Platform. The Florida Platform rocks were deposited on top of an eroded surface of a crystalline rock complex, which is known collectively as the Florida basement rocks. The Florida basement rocks, consisting of low-grade metamorphics and igneous intrusives, occur several thousand feet below the land surface and are Precambrian, Paleozoic, and Mesozoic in age.

The base of the sedimentary rocks in the Florida Platform is made up of a thick, primarily carbonate sequence deposited from the Jurassic through the Paleocene. Starting in the Miocene and continuing through the Holocene, siliciclastic sedimentation became more dominant.

The east coast of Florida is bounded by a continental shelf that is moderately broad and slopes gently to the north but becomes both narrower and steeper to the south, toward Cape Canaveral. Cape Canaveral is a prominent feature, a large cuspate foreland or promontory that projects 13 miles seaward of the main coastal trend and strongly influences the orientation and sedimentation patterns along at least 80 miles of Florida's east coast. Cape Canaveral itself may have been formed by converging littoral transport along the coast (Davis 1997).

2.1.3.2 Site Geology

CCAS is situated on Canaveral Peninsula, which is on the east side of Merritt Island, a barrier island in Brevard County on the Atlantic coast of Florida. Facility 1381 is located in the central portion of CCAS. The topography at Facility 1381 is relatively flat, with ground elevations ranging from approximately 5 to 10 feet above mean sea level (msl) (Parsons 1999a). The topography consists of long, northeast-southwest trending, low rises that are most likely depositional features associated with accretion of the barrier island. Vertical relief in the area is limited to shoulders of drainage canals that slope from the ground surface to the canal bed. Drainage canals are located 200 feet southwest (Landfill Canal) and 2,500 feet north (Northern Drainage Canal) of the GCW; both flow westward toward the Banana River.

The site geology is presented in cross-section A-A', which is shown as Figure 3. Based on previous work at the site conducted by Parsons (2000), the geology at Facility 1381 consists of unconsolidated sediments to a depth of at least 60 feet bgs. The upper 15 feet consists of poorly sorted, dominantly coarse shell material and coarse to medium sand.

The average grain size of the sand fraction decreases and the silt and clay content increases from depths of 35 feet to approximately 50 feet below ground surface (bgs). A 5-foot-thick unit of fine to very fine-grained sand and silt occurs from 35 to 40 feet bgs. Shell fragments and coarse sand occur with varying amounts of clay from approximately 40 to 50 feet bgs.

A layer of firm clay, which may be continuous across the site, has been encountered at a depth of 50 feet bgs.

2.1.4 Regional and Site Hydrogeology

The regional and site hydrogeology are discussed in the following subsections.

2.1.4.1 Regional Hydrogeology

Regional hydrostratigrapic units that occur near Cape Canaveral are presented in Figure 4 and are described below.

Surficial Aquifer. The uppermost water-bearing unit near the site is the surficial aquifer, which is unconfined and consists primarily of unconsolidated materials. The surficial aquifer system is a shallow, nonartesian aquifer, which occurs over much of eastern Florida but is not an important source of groundwater because better supplies are generally available from other aquifers. The extent of the surficial aquifer is shown in Figure 5.

The surficial aquifer system extends to a depth of approximately 50 to 60 feet bgs near CCAS. The surficial aquifer is described as consisting of fine to medium quartz sand that contains varying amounts of silt, clay, and loose shells that are post-Miocene in age. In coastal areas, such as at CCAS, the surficial aquifer may also consist of partially cemented shell beds or coquina. The depth of the water table in the surficial aquifer ranges from at or near the land surface in low-lying areas to tens of feet below the land surface in areas of higher elevations.

The most important function of the surficial aquifer is to store water, some of which recharges the underlying Floridan aquifer. The surficial aquifer is little used as a source of drinking water since its permeability is low, resulting in relatively limited yield to wells, when compared with the Floridan aquifer system. The surficial aquifer is used to supply potable drinking water only in coastal areas where the underlying Floridan aquifer may be brackish (Miller 1986).

The sands of the surficial aquifer generally grade into less permeable clayey or silty sands or low-permeability carbonate rocks at depths of usually less than 75 feet below the land surface. These rocks act as a confining unit for limestones that compose the underlying Floridan aquifer system. This upper confining unit of the Floridan aquifer system, as it is known, is generally composed of the middle Miocene-aged Hawthorn Formation, low-permeability rocks that in most places separate the Floridan aquifer from the surficial aquifer.

Floridan Aquifer. The Floridan aquifer system is a nearly vertically continuous, very thick sequence of generally highly permeable carbonate rocks. The degree of hydraulic connection of units that make up the Floridan aquifer depends primarily on the texture and mineralogy of the rocks that constitute the system (Miller 1986). The Floridan aquifer system is composed of sequences of limestone and dolomitic limestone.

The top of the Floridan Aquifer is defined as the first occurrence of vertically persistent, permeable, consolidated carbonate rocks. Rocks at the top of the Floridan aquifer at CCAS occur at an elevation of approximately 150.0 feet below msl or at a depth of 160 feet bgs. The top unit of the Floridan aquifer at CCAS is composed of the Ocala Limestone of late Eocene age, and the Floridan aquifer system ranges in thickness from 2,600 to 2,700 feet. The base of the Floridan aquifer system is defined as the first occurrence of anhydrite or presence of a gradational contact of generally permeable carbonate to much less permeable gypsiferous and anhydritic rocks. These low-permeability rocks, known as the lower confining unit of the Floridan aquifer system, everywhere underlie the Floridan. The transmissivity of the Upper Floridan aquifer that underlies CCAS is estimated to be 50,000 to 100,000 square ft/day (Miller 1986).

Geologic formations that make up the Floridan aquifer in east-central Florida are, from top to bottom, the Suwanee Limestone (where present), Eocene in age; the Ocala Limestone (where present); the Avon Park Formation; and, in some areas, all or part of the Oldsmar Formation. Paleocene rocks of the Cedar Keys Formation usually are recognized as forming the base of the Floridan aquifer system, except in areas where the upper part of the Cedar Keys Formation is permeable (Tibbals 1990).

2.1.4.2 Site Hydrogeology

The shallow aquifer zone at Facility 1381 is part of the surficial aquifer, which, as described previously, is a regionally unconfined water table aquifer. The water table at CCAS generally occurs at depths ranging from 3 to 15 feet bgs. The water table occurred at approximately 8 feet bgs near the area where the groundwater circulation well was installed.

Flow of shallow groundwater at CCAS is controlled by an engineered drainage system consisting of a series of man-made canals, which were installed to reclaim land by lowering the water table. Surface water at the site drains through the canals and discharges into the Banana River, which is located west of CCAS. Closest to Facility 1381 is Landfill Canal, which is located 200 feet southwest; the Northern Drainage Canal is located about 2,500 feet due north of Facility 1381.

The canals strongly influence flow of shallow groundwater at the site. A groundwater divide is indicated in the vicinity of the GCW, as evidenced by groundwater flow to the southwest toward Landfill Canal, as well as to the northeast in the direction of the Northern Drainage Canal. Surface water elevations measured in the canals are lower than adjacent shallow groundwater elevations, suggesting groundwater discharge to the canals (Parsons 2000).

The upper part of the surficial aquifer at Facility 1381 has been delineated into shallow and deep aquifer zones for this evaluation. The shallow aquifer zone is defined as the upper saturated portion of the aquifer, from the water table to the contact of the coarse-grained shell and coarse to medium grained sand unit that occurs approximately 15 feet bgs. The shallow aquifer zone is approximately 8 feet thick. The deep aquifer zone is made up of medium to fine sand units, which occur at depths of 15 to 30 feet bgs. The shallow and deep aquifer zones are depicted on Figure 3, cross-section A-A'.

The hydraulic conductivity of the surficial aquifer at Facility 1381 was previously measured using rising head slug tests at a monitoring well pair, 1381MWS09 (screened 7.5 to 12.5 feet bgs) and 1381MWI09 (screened 30 to 35 feet bgs), located 55 feet southeast of the GCW. The calculated hydraulic conductivity values are 11.6 ft/day for the shallow well and 0.4 ft/day for the deep well.

Slug testing in piezometers near the GCW yielded hydraulic conductivity values of 17.8 to 24.2 ft/day in piezometer 4PZS (screened 6.5 to 9.5 feet bgs) in the shallow aquifer zone and 0.1 to 0.2 ft/day in piezometers 2PZD (screened 21.3 to 24.6 feet bgs) and 6PZD (screened 22.7 to 26 feet bgs) in the deep aquifer zone. The groundwater velocity in the shallow aquifer zone under natural flow conditions is estimated at 0.21 ft/day (Parsons 2000).

Values for hydraulic conductivity obtained from aquifer testing conducted in September 2000 are presented in Appendix A, the Hydrogeological Investigation Report. Based on the pumping test data, the hydraulic conductivity of the estimated saturated upper portion of the aquifer (42 feet thick) ranges from 43 to 53 ft/day.

2.1.5 Site Contamination

Contamination in soil and groundwater at Facility 1381 has been attributed to historical waste disposal practices. A plume of contaminants in groundwater, consisting primarily of TCE and associated degradation products including cis-1,2-dichloroethene and vinyl chloride, has been detected at the site. The plume is 110 acres in areal extent and is 2,500 feet long. The axis of the plume is elongated to the north-northeast.

The maximum concentration of TCE detected to date in the suspected source area is 342,000 micrograms per liter (µg/L) (Parsons 1999b). Concentrations of TCE measured in samples from the source area have been lower during more recent sampling rounds.

2.2 OBJECTIVES OF EVALUATION

The SITE evaluation was designed to address primary and secondary objectives selected for the GCW technology. These objectives were selected to provide potential users of the GCW technology with technical information on the groundwater circulation cell established by the treatment system. One primary and four secondary objectives were selected for the SITE evaluation of the GCW technology and are listed below:

Primary Objective:

P1 Evaluate the flow sensor's ability to detect the horizontal extent of the GCW groundwater circulation cell based on a change in the groundwater velocity criterion of 0.1 foot per day (0.03 meter per day)

Secondary Objectives:

S1 Evaluate the reproducibility of the groundwater velocity sensor data

S2 Evaluate the three-dimensional groundwater flow surrounding the GCW

S3 Document the operating parameters of the GCW.

S4 Document the hydrogeologic characteristics at the treatment site.

The objectives were evaluated by collecting in situ groundwater sensor data and conducting a series of aquifer hydraulic tests. Data were collected and analyzed using the methods and procedures summarized in Section 2.3 to meet the objectives of the evaluation.

2.3 METHODOLOGY OF EVALUATION

This section describes the procedures used to collect and analyze data from the groundwater flow sensors.

2.3.1 Placement and Installation of Groundwater Flow Sensors

The strategy for placement and installation procedures for the groundwater flow sensors is described in the following subsections.

2.3.1.1 Placement of Sensors

Seven groundwater flow sensors manufactured by HydroTechnics were installed during the week of June 24, 2000. The flow sensors were installed in two separate clusters southeast of and in two separate clusters southwest of the GCW.

Data collected from the flow sensors were used to evaluate both the horizontal extent of recirculation and the overall three-dimensional groundwater flow pattern that surrounds the GCW. Modeling of the circulation cell performed by the Oregon Graduate Research Institute was used to predict the horizontal extent of the circulation cell and to select the locations of the flow sensors. The modeling predicted that groundwater in the upper portion of the treatment zone would flow radially away from the GCW, and that groundwater in the lower portion of the treatment zone would flow radially toward the GCW. The results of modeling were also used to show that flow velocities surrounding the GCW would decrease with distance from the GCW. The modeling results indicated that the extent of circulation at velocities that exceeded 0.05 ft/day appeared to be limited to a radial distance of 10 feet from the GCW. In addition, induced groundwater flow velocities near the GCW were predicted to exceed 2.0 ft/day at a distance of 5 feet from the GCW. Based on the modeling results, the most appropriate zone for installation of flow sensors is between 5 feet and 10 feet from the GCW.

The velocity range of groundwater flow that can be accurately measured by the groundwater flow sensors is between 0.01 and 2.0 ft/day, based on the manufacturer’s specifications. Based on this criterion and the results of modeling for the GCW, two of the flow sensor clusters were installed 7.5 feet from the GCW, and two of the flow sensor clusters were installed 13 to 15 feet from the GCW. This strategy for placement of the sensors took into account the measurement range of the sensors of 0.01 to 2.0 ft/day to ensure that changes in the velocity of groundwater flow can be accurately measured.

The sensors were installed in relation to the assumed hydraulic gradient, which was determined to be to the southwest. Three flow sensors were placed to the southwest (assumed downgradient) of the GCW. Another four flow sensors were placed to the southeast (assumed cross gradient) of the GCW (Figure 6).

2.3.1.2 Installation of Flow Sensors

The sensors were installed using a hollow-stem auger drilling rig equipped with 4.25-inch-inner-diameter augers. The sensor was then lowered through the inner annulus of the drill pipe by attaching it to a 2-inch-diameter schedule 40 PVC well casing. The well casing was used to house the sensor cables in addition to providing a platform that enabled the field crew to lower the sensors into the borehole. After the sensor was seated at the bottom of the boring, the auger flights were retracted, allowing the saturated unconsolidated aquifer matrix to collapse around the flow sensor.

2.3.2 Methodology for Evaluation of Data from Flow Sensors

Evaluation of the flow sensors consists of using the data collected to assess the presence of a three-dimensional groundwater flow regime or circulation cell. The circulation cell is induced when the GCW is in recirculation mode. For this evaluation, evidence for the existence and the extent of the circulation cell was as follows:

(1) Increases in horizontal groundwater Darcy velocities (hydraulic conductivity times hydraulic gradient) in excess of 0.1 ft/day.

(2) Changes in vertical groundwater Darcy velocities and the vertical hydraulic gradient.

(3) Changes in direction of groundwater flow such that flow is away from the upper screen of the GCW in the shallow aquifer zone and toward the lower screen of the GCW in the deep aquifer zone.

The evaluation was designed to assess changes in the velocity of groundwater flow (magnitude and direction) measured by the flow sensors.

Data from the flow sensors were presented in hydrographs as horizontal and vertical velocity versus time, plotted in map view to show the horizontal component of velocity and direction, and plotted in cross-section view showing resulting groundwater velocities and directions of groundwater flow. In addition, the data on groundwater velocity that represent each operational period were tabulated.

The groundwater flow sensors were installed in linear arrays at varying distances and depths from the GCW in order to achieve the primary objectives defined in Section 2.2. Velocities and directions of groundwater flow within the circulation cell of the GCW were measured using seven in situ groundwater flow sensors in each cluster. The horizontal change in velocity was calculated by subtracting the measured flow velocity. The changes in velocity of flow were calculated for each operational mode using the data set that began when steady-state flow conditions had been established. Locations where changes in the velocity of flow were equal to or greater than 0.1 ft/day were considered to be within the extent of the circulation cell created by the GCW.

The three-dimensional groundwater flow that surrounds the GCW was evaluated to identify overall changes in direction of groundwater flow and velocity attributed to the GCW. The three-dimensional groundwater flow pattern was depicted qualitatively using hydrographs, horizontal flow vector maps, and resulting flow velocity projected onto cross-sections. The three-dimensional groundwater flow was depicted separately for each operating condition.

The following process control data collected by AFCEE during operation of the GCW evaluation were used to document the operating parameters of the GCW: (1) water pumping rate, (2) duration of system operation, and (3) description of any system shutdowns.

Hydrogeologic data collected during previous investigations at Facility 1381 were reviewed to develop a site hydrogeologic conceptual model. A series of aquifer tests were also conducted to evaluate the hydraulic parameters in the shallow aquifer zone such as hydraulic conductivity (K), transmissivity (T), storativity (S), and specific yield (S_y). These data were used in combination with data from the flow sensors to assess groundwater flow patterns within the treatment zones.

2.4 QUALITY ASSURANCE AND QUALITY CONTROL PROGRAM

This section discusses QC measures that were used during installation and operation of the flow sensors.

2.4.1 Calibration Procedures for Flow Sensors

All flow sensors undergo a two-step calibration process. The first calibration step occurs at the factory and involves certifying that all thermistors measure temperature differences as small as 0.01 C in a water bath and creating a signal signature, or calibration file. The second calibration step occurs in the field, involving mathematically correcting for recorded lithology-induced thermal variations. The end result is a probe that records the thermal distribution over its surface independent of lithology and as measured against a known standard

2.4.2 Installation Procedures for Flow Sensors

QA/QC procedures implemented during installation of the sensors ensured that the exact location, depth, and orientation of each sensor were recorded, and that the sensors were operating properly after they were installed. The procedure for installation included recording the number designated by the factory from each sensor and labeling each sensor with an appropriate EPA identification number. Each EPA identification number included the project name, the work assignment number, the number designated by the factory, the relationship to the GCW, and a two-digit consecutive number.

A reference line on each sensor was translated to the surface indicating its orientation. The sensors were attached to the top of the PVC casing. The line was marked on the side of the PVC casing so that the orientation of the sensor would be identified at the ground surface. When installation was complete, the orientation of the sensor was verified using a compass that had been corrected for declination. HydroTechnics requires the orientation of the sensor as an input to the data processing software. After the sensors were installed and oriented, the electrical resistance of each flow sensor was checked to make sure that it was working properly. The GCW and the locations of the flow sensors were surveyed and the horizontal coordinates were used to calculate the exact distances of the flow sensors from the GCW.

2.4.3 Data Processing Procedures

The probes generate raw minivolt data that HTFLOW© software interprets. QA/QC procedures used in processing raw millivolt data used the two reference resisters built into each sensor. The two reference resisters are fixed and read constant values regardless of the temperature or position of the sensor in the subsurface. The data loggers collect and store readings from the reference resisters as part of the main data file. The reference resisters serve as a check to ensure that data being collected are accurate and are not subject to any electrical interferences.

2.5 MODIFICATIONS TO THE TECHNOLOGY EVALUATION PLAN

The TEP (Tetra Tech 2000) specified that the flow sensors would be installed near the GCW and in relation to the natural flow gradient. Two groups of flow sensors, consisting of deep and shallow clusters, were to be installed downgradient of the GCW, and two clusters were to be installed cross-gradient from the GCW. The sensors were installed assuming a natural flow gradient to the southwest. Groundwater elevation data collected in 2000, however, suggest that the horizontal hydraulic gradient is very low and that the direction of groundwater flow near the GCW varies. Evidence also indicates that a groundwater flow divide is present near the GCW. Because a constant hydraulic gradient is absent, the relationship of the locations of the flow sensors to the natural direction of groundwater flow cannot be established.

The flow sensors were installed at depths that varied from the plan. The deep sensors were installed 1 to 2 feet shallower than was planned because of subsurface conditions encountered during their installation. Soil samples collected from the deeper portion of the aquifer showed an increase in fine-grained materials. The sensors were installed in the shallower, more permeable portion of the aquifer to ensure flow around the sensor would be measurable.

To evaluate the flow in the upper screened interval, it was therefore decided in the field to install the shallow sensors at a depth of approximately 1 foot (0.3 meters) below the existing groundwater surface. The shallow sensors were installed at a lower depth because the groundwater level at the site was lower than was anticipated. Florida was experiencing a drought and static water levels were several feet lower than had been reported in previous site investigations. The shallow flow sensors were installed with less than manufacturer recommended submergence because initial modeling results indicated that there would not be measurable flow deeper than 6.6 feet (2 meters) into the aquifer 6.6 feet (2 meters) radial distance from GCW. With effort the manufacturer was able to interpret shallow sensor data.

In most cases, the radial distances of the flow sensors from the GCW were within 0.25 feet of those specified in the plan. The clusters of flow sensors were installed along a line such that the deep flow sensors were farther away from the GCW than were the shallow flow sensors. As a result, the following exceptions were noted with respect to installation distances of the flow sensors. Deep flow sensor C02 was installed 1.5 feet farther away from the GCW than was specified in the plan. Deep flow sensor D02 was installed approximately 1.75 feet farther from the GCW than was specified in the plan. Shallow flow sensor C03 was installed 0.5 feet closer to the GCW than was specified in the plan.

While the technical data collection performed during the demonstration was generally consistent with the requirements of the TEP, except as noted above, the wording of the primary objective and first secondary objective were slightly revised for the purposes of clarity in reporting the results of the demonstration. The TEP reports the primary objective as to evaluate the horizontal extent of the groundwater circulation cell. This TER reports the primary objective more accurately as to evaluate the flow sensor's ability to detect the horizontal extent of the groundwater circulation cell. The first secondary objective was reworded to more accurately reflect the objective to evaluate the reproducibility of the groundwater velocity data obtained from the flow sensors; rather than the original wording, which was to evaluate the precision of the sensors.

3.0 GROUNDWATER CIRCULATION WELL SYSTEM

This section describes the GCW system, including the design and principle of operation, GCW installation, hydraulic conditions near the GCW, and operational modes of the GCW. Table 1 is a chronology of field events associated with installation and operation of the GCW.

3.1 DESIGN AND PRINCIPLE OF OPERATION

The WEI GCW is an in situ groundwater remediation system designed to simultaneously circulate and strip VOCs from groundwater in the aquifer. In the WEI system, airlift pumping moves groundwater upward from a screen in the lower section of the well. Air is pumped to the bottom of the well using a blower, reducing the weight of the water column. Groundwater and air are then lifted to an upper screen, where the air strips VOCs and the groundwater is allowed to discharge back into the aquifer. The air stream used to strip VOCs is extracted from the wellhead and is treated before it is released to the atmosphere. Groundwater that re-enters the aquifer via the top screen flows vertically downward and can be recaptured by the GCW, where it is treated again. The groundwater flow regime developed by the GCW is termed a circulation cell, and its characteristics are critical to the effectiveness of the technology. Key parameters of the circulation cell are its size, or radius, and its percent capture (Parsons 1999a).

For the demonstration at CCAS, the design of the GCW was modified to include an eductor pipe. The eductor pipe was installed inside the GCW to prevent air bubbles from escaping from the lower screened interval and into the surrounding aquifer. The addition of the eductor pipe allows air-lift pumping operation of the GCW without exposing the GCW intake screen (lower screen) to air bubbles.

3.2 INSTALLATION OF GROUNDWATER CIRCULATION WELL[1]

The GCW system at CCAS Facility 1381 was installed in November 1999. A schematic diagram of the GCW is presented as Figure 7. The GCW system is a 6-inch-diameter PVC well casing with two separate, wire-wrapped PVC well screens, installed to a total depth of 35 feet bgs. The upper screened interval is 5 feet long and was installed from 5 to 10 feet bgs using a 20-slot (0.020-inch), wire-wrapped PVC screen. The lower screened interval is 10 feet long and was installed from a depth of 20 to 30 feet bgs using a 10-slot (0.010-inch), wire-wrapped PVC screen. A 5-foot long sump was installed at a depth

[1] All pipe diameters and lengths are listed in American Standard Engineering units. Please see page xiv for conversion factors for metric units.

of 30 to 35 feet bgs, below the intake screen of the lower screened interval, to collect sediments. The entire sub-surface system was installed in a 14-inch diameter boring.

A filter pack that consisted of 20/45 silica sand was installed in the annulus around the intake (lower) screen from 18 to 35 feet bgs. Coarser-grained, 6/20 silica filter sand was installed in the annulus around the outflow (upper) screen from 0 to 11 feet bgs. The filter sand was installed using a tremie pipe and was surged every 5 feet to ensure that the filter pack settled. Alternating layers of bentonite clay and silica sand were poured in the annulus around the middle blank casing section between 11 and 18 feet bgs. The bentonite clay seals were installed to prevent downward flow of water through the annulus.

The eductor pipe was constructed of 4-inch-diameter PVC to simulate the airlift performance of a 4-inch-diameter GCW. The eductor pipe is perforated from 3 to 5.5 feet bgs and from 29.5 to 31 feet bgs. The perforations consist of 0.5-inch diameter holes in four lines spaced radially around the pipe, approximately 4 inches apart vertically.

Two piezometers were installed within the sand pack of the 14-inch diameter GCW boring. The upper piezometer, GCWS, was screened from 7 to 8 feet bgs, adjacent to the upper screened interval of the GCW. The lower piezometer, GCWD, was screened from 24.5 to 25.5 feet bgs, adjacent to the lower screened interval of the GCW. Figure 6 shows piezometers GCWS and GCWD in relation to the GCW.

Four piezometer pairs, each consisting of 1.5-inch-diameter shallow and deep piezometers (2PZS/2PZD, 3PZS/3PZD, 4PZS/4PZD, and 6PZS/6PZD) were installed within a 30-foot radius of the GCW. Except for 6PZS, these piezometers were used as observation wells during aquifer hydraulic testing. The piezometers were screened at intervals of approximately 6 to 9.5 feet (shallow) and 22 to 26 feet (deep) bgs.

3.3 HYDRAULIC CONDITIONS NEAR THE GROUNDWATER CIRCULATION WELL

This section discusses hydraulic conditions near the GCW by defining the aquifer zones screened by the GCW and describing the natural patterns of groundwater flow near the GCW.

3.3.1 Definition of Screened Aquifer Zones

The upper screen of the GCW was installed at a depth of 5 to 10 feet bgs and is completed in the shallow aquifer zone. The shallow aquifer zone consists predominantly of coarse shell fragments and coarse to medium sand with little or no silt and no clay.

The lower screen of the GCW was placed at a depth of 20 to 30 feet bgs in the deep aquifer zone. The lithology of the deep aquifer zone is described as predominantly medium to very fine sand with little or no silt or clay, possibly containing significant amounts of shell fragments. A lower part of the deep aquifer zone consists of fine sand and silt.

Piezometer pairs near the GCW were installed in either the shallow (S-series) or the deep (D-series) aquifer zones.

3.3.2 Natural Groundwater Flow Conditions

Site groundwater elevations measured in 1996 indicated that site groundwater appears to be affected by a northwest-trending groundwater divide (Parsons 2000). The divide directs groundwater flow to the southwest toward Landfill Canal, and to the northeast. The groundwater divide is present in both the shallow and deep aquifer zones, although the location of the divide may differ in the two aquifer zones. As a result of the divide, direction of groundwater flow beneath Facility 1381 may be temporally variable, as the groundwater divide moves laterally in response to changes in water levels in the canal and infiltration recharge rates.

Data on groundwater elevations were collected in the deep and shallow piezometers near the GCW during natural flow conditions on separate dates in April, June, and July 2000 (Parsons 2000). Table 2 summarizes directions of groundwater flow. The data indicate that directions of flow in both the shallow and deep zones reversed during the 4-month period. The direction of groundwater flow in the shallow aquifer zone shifted between flow to the northwest and flow to the south and southeast. Similarly, the direction of groundwater flow in the deep aquifer zone shifted between flow to the north/northwest and flow to the southeast. However, the direction of flow in the deep and shallow aquifer zones were the same in April and mid-June, but were different from each other in late June and early July. The combination of the low horizontal hydraulic gradient and recharge effects of the canals most likely cause constant fluctuations in the direction of groundwater flow near the GCW.

The information presented in Table 2 indicates that the directions of groundwater flow in both the shallow and deep aquifer zones are variable and can vary between the two aquifer zones at the same time. The information confirms that a groundwater flow divide exists near the GCW. As a result, no dominant direction of flow can be identified in either aquifer zone.

3.4 GCW OPERATIONS

During the demonstration the GCW was operated in four operational modes: GCW circulation, pump-and-treat testing, aquifer testing, and dipole flow testing (DFT). This section describes GCW operation in each mode.

3.4.1 GCW Circulation

AFCEE operated the GCW in circulation mode during the spring and summer of 2000. The setup of the GCW in circulation mode is shown as a schematic diagram in Figure 8. An air supply pipe, constructed of 0.75-inch PVC, was inserted in the GCW within the eductor pipe. Pressurized air was then supplied to the well via piping fitted with a pressure gauge and a flow meter, which measured airflow to the GCW. A section of 1.5-inch-diameter PVC pipe was attached to the end of the air supply pipe to direct airflow upward within the eductor pipe. Air was injected into the GCW at a depth of approximately 29 feet bgs.

After several weeks of operation in this mode, evidence of scaling or accumulation of calcium carbonate was noted in the GCW. The scaling occurs when carbon dioxide is stripped from the water as it flows through a well, when the pH of the water increases to the point that calcium carbonate is oversaturated and begins to precipitate. As a result, an acid drip system was installed, which began operating on May 5, 2000, to maintain the pH of the water and reduce scaling. The acid drip system consisted of a 5-gallon acid container and a metered pump that discharged acid to the top of the air supply pipe. A hydrochloric acid solution with a pH of slightly above 2.0 standard units was injected into the well at the air discharge point, where the surging action of the airlift pumping would promote maximum mixing. The acid injection rate was adjusted in an attempt to maintain the pH of the outflow water as near as possible to the pH of the inflow water. The 5-gallon storage container was subsequently replaced with a 30-gallon container to permit increases in the rate of acid addition. The acid injection system is shown schematically in Figure 8.

During the circulation mode of operation, AFCEE conducted three types of tracer tests to assess the performance of the GCW. Flow rate testing using bromide was performed to provide a direct measure of flow through the GCW. A second test using sulphur hexafluoride (SF_6) assessed the extent of recirculation for flow out of the upper GCW screen back to the lower well screen. A third test using fluorescent dye evaluated movement of water away from the GCW and into the aquifer.

3.4.2 Pump-and-Treat Testing

AFCEE conducted groundwater pump-and-treat tests both before and after operation of the GCW in circulation mode to allow a comparison of the circulation operation results with results obtained using a more conventional technology (pump-and-treat). A schematic diagram of the pump-and-treat system is shown in Figure 9. A ½-horsepower (HP) electric submersible pump was installed in the 4-inch ID eductor pipe in the lower screened interval of the GCW at a depth of approximately 28 feet bgs to conduct the pump-and-treat operation.

Operation of the GCW during the pump-and-treat test consisted of pumping water from the lower screened interval. The extracted water was pumped into a holding tank and then treated using an air-stripping unit. The treated effluent was then piped to an infiltration zone for discharge by a sprinkler system.

3.4.3 Aquifer Hydraulic Testing

EPA conducted aquifer hydraulic testing using the lower screened interval of the GCW as the pumping well. An inflatable packer was used to isolate the two screened intervals to facilitate pumping from only the lower screened interval. Figure 10 is a schematic diagram of the aquifer testing system at the GCW.

Aquifer hydraulic tests consisted of a step drawdown test, a DFT, and a constant-rate pumping test. Objectives and results of the aquifer testing are presented in Appendix A, the Hydrogeological Investigation Report.

3.4.4 Dipole Flow Testing

EPA conducted multiple DFTs using the GCW on September 14 and 18, 2000. Figure 11 is a schematic diagram of the setup for the DFTs. The DFTs were conducted by simultaneously pumping water from the lower screened interval in the deep aquifer zone and injecting the discharged groundwater into the upper screened interval in the shallow aquifer zone. The pumping rate was equal to the injection rate during each of the DFTs. Water levels in piezometers GCWD, GCWS, 2PZD, 2PZS, 3PZD, 3PZS, 4PZD, 4PZS, and 6PZD were monitored using Insitu® mini-TROLL pressure transducers and data loggers.

Five separate tests were completed at different flow rates during the DFTs conducted on September 14, 2000. Groundwater was pumped and injected simultaneously at rates of 2.3, 3.7, 6.0, 8.8, and 4.8 gallons per minute (gpm) in periods that lasted 30 minutes each, except for the final test, which lasted 90 minutes. A recovery period of 30 minutes was allowed between each test. The 30-minute recovery period after each DFT was considered adequate because relatively fast recovery in the water level was observed in the lower and upper screened intervals of the GCW during the step-drawdown tests. Groundwater hydrographs for piezometers GCWS and GCWD during Dipole Tests 1 through 5 (see Appendix A) demonstrate that the 30-minute recovery period between tests was adequate.

An additional DFT (Dipole Test 6) was conducted on September 18, 2000 using a higher flow rate and a longer test period, specifically pumping and injecting groundwater at a rate of 12.5 gpm for 142 minutes. The DFT was stopped prior to its full duration because of a power failure and, as a result, logarithmic data for the water level recovery could not be collected for the early portion of the test. A second high-flow/long-duration DFT (Dipole Test 7) was conducted later on September 18, at a pumping and injection rate of 12.5 gpm for 360 minutes.

4.0 IN SITU GROUNDWATER FLOW SENSORS

This section describes the in situ groundwater flow sensors and discusses their operation, data collection, and data evaluation.

4.1 DESCRIPTION OF GROUNDWATER FLOW SENSORS[1]

The groundwater flow sensors installed at CCAS were developed at Sandia National Laboratories and manufactured by HydroTechnics, both of Albuquerque, New Mexico. The flow sensors are in situ instruments that use a thermal perturbation technique to directly measure the velocity of groundwater flow in unconsolidated, saturated, porous media. The flow sensors differ from other devices to measure groundwater velocity in that they are in direct contact with the unconsolidated aquifer matrix where the flow is to be measured, thereby avoiding borehole effects. The flow sensor is a thin, cylindrical device that is permanently buried at the depth where the velocity of groundwater flow is to be measured.

The flow sensors operate on the principle that if the heat flux out of the cylinder is uniform over its surface, the temperature distribution on the surface of the cylinder will vary as a function of the direction and magnitude of groundwater flow past the cylinder. Because heat introduced into the formation by the heater is advected by flow of fluid around and past the instrument, relatively warm temperatures are sensed on the downstream side of the probe and relatively cool temperatures are detected on the upstream side (Ballard 1996). Thus, the direction and magnitude of groundwater flow are recorded as those locations in the cylinder where the temperature gradients are the highest.

Each flow sensor consists of a cylindrical heater, 30 inches long by 2 3/8 inch in diameter with an array of 30 calibrated temperature sensors on its surface. When the instrument is installed directly in contact with the unconsolidated aquifer matrix and activated, the heater warms the aquifer matrix and groundwater around the instrument to 20 to 30 ^{o}C above background temperature. The distribution of temperature on the surface of the sensor is independent of azimuth and symmetrical about the vertical midpoint of the sensor in the absence of any flow. When there is flow past the sensor, the distribution of the surface temperature is perturbed as the heat emanating from the sensor is advected by the moving fluid.

[1] All pipe diameters and lengths are listed in American Standard Engineering units. Please see page xiv for conversion factors for metric units.

The flow sensors are designed to be installed into the subsurface through the center of a hollow-stem auger flight, typically through a standard 4.25-inch-inner-diameter hollow-stem auger. Each sensor is connected to the surface by electrical cables housed in 2-inch schedule 40 PVC well casing. One electrical cable provides power for the 40-ohm electrical resistance heaters on each sensor. Seventy watts of power input are required to operate a 57-volt direct current (DC) power supply at 1.4 amps. The thermistors within the sensors have a normal resistance of 1 megaohm at 25 ^{o}C, about 2.5 megaohm at 10 ^{o}C, and about 125 killiohm at 70 ^{o}C. Table 4 provides a summary of the specifications for the flow sensors.

Data loggers collect and store data as millivolt readings derived from the thermistors. The data logger can be programmed to collect data as frequently as once every minute. Once data are collected, they can be manually downloaded in the field using a laptop computer or they can be acquired remotely through a modem. The data can be interpreted via HydroTechnics' proprietary software, HTFLOW© (HydroTechnics 1997). The software accepts the raw millivolt data and converts them into temperature data; temperature data can then be manipulated and simulated to calculate velocities of groundwater flow using an inverse technique. The resulting output includes horizontal and vertical groundwater velocity vectors and an azimuth for horizontal direction of flow.

4.2 INSTALLATION OF GROUNDWATER FLOW SENSORS

Seven flow sensors were installed in the deep and shallow aquifer zones in two separate clusters. The flow sensors were installed from June 26 to June 28, 2000; data collection and data downloading began by July 1, 2000. Specifications for installation of the flow sensors are provided in Table 5.

Locations of the sensors in the deep and shallow aquifer zones relative to the GCW are shown in Figure 6. Four flow sensors (D-series) were installed southeast of the GCW, and three flow sensors (C-series) were installed southwest of the GCW. The radial distances of the flow sensors from the GCW were selected based on modeled predictions of the extent of the circulation cell created by the GCW. The modeling results were also used to predict the velocity of groundwater flow in the area that surrounds the GCW. A general criterion was established to define the area of the GCW circulation cell where changes in the velocity of groundwater flow either horizontal, vertical, or both of more than 0.1 ft/day occur. Based on this criterion and on the results of the GCW modeling, two of the flow sensor clusters (C01/C02 and D01/D02) were installed within the predicted radius of the circulation cell, 7.5 feet from the GCW. The other two flow sensor clusters (C03/C04 and D03) were installed at 13 to 15 feet from the GCW.

The depths of the flow sensors were selected in reference to the upper and lower screened intervals of the GCW. The upper screen of the GCW was installed from 5 to 10 feet bgs, and the lower screen of the GCW was installed from 20 to 30 feet bgs. When the flow sensors were installed, the water table was approximately 8 feet bgs, based on a water level measurement in piezometer 3PZS made on July 7, 2000 (Parsons 2000). The shallow flow sensors were installed at depths so that the top of each sensor was approximately 8.5 feet bgs, or about 0.5 foot below the static water table. The deep flow sensors were installed at depths so that the top of the sensor was approximately 17 to 19 feet bgs. Based on recommendations by HydroTechnics, the deep sensors were installed first, followed by the shallow sensors. This method allowed the formation time to settle around the deep sensors before drilling was resumed in their immediate vicinity.

When the soil borings were advanced for flow sensor installation, soil samples were collected at changes in lithology or at 5-foot intervals using a 24-inch-long, split-spoon sampler. The soil samples were used to assess subsurface conditions and for lithologic logging. Soil samples and cuttings were logged using the Unified Soil Classification System. In addition, the bottom 4 feet of each boring was continuously sampled to ensure that the 30-inch long sensors would be positioned in a relatively homogenous lithologic section of the soil column. As such, the depths proposed for the sensors were adjusted based on the subsurface conditions encountered during installation to ensure a homogenous lithologic section in the vicinity of the flow sensor.

4.3 OPERATION OF GROUNDWATER FLOW SENSORS

The flow sensors were connected to a control panel to provide electrical power for their heaters and to store outputs in a data logger. Two Campbell Scientific CR-10X data loggers were used to record sensor data and were connected to a modem for remote data access. One data logger was dedicated to the four cross-gradient sensors, and the other data logger was dedicated to the three downgradient sensors. Starting on July 1, 2000, the data loggers recorded data from each sensor every 30 minutes for the 6-month evaluation period. The data from the flow sensors were collected at 2-minute intervals during the aquifer testing period from September 11 to September 20, 2000.

Data from the flow sensors were being collected and stored as millivolt readings, derived from the thermistors that cover the sensors. Failure of a power strip at the beginning of September 2000 (potentially the result of lightning strikes) caused all of the flow sensors to power down. The failure was discovered and the power strip was replaced; the flow sensors were restarted on September 11, 2000.

Based on the memory capacity of the data loggers and the proposed frequency of data collection, each data logger rewrites over old data about every 2 months. Each data logger was downloaded remotely every 30 days using a modem to ensure that no data would be lost. This schedule allowed approximately 30 days to collect data manually in the event that remote access capabilities were lost. The raw sensor data was processed using HTFLOW© software. A copy of the HTFLOW© software manual was included as Appendix A in the TEP/QAPP (Tetra Tech 2000).

4.4 LIMITATIONS OF FLOW SENSOR DATA AND DATA MANIPULATION

The process of simulating and manipulating data from the flow sensors yields a three-dimensional vector for velocity of groundwater flow, which is then converted to the horizontal Darcy flow rate, vertical Darcy flow rate, and the azimuthal direction of groundwater flow. The limitations of data manipulation are discussed in the following sections.

4.4.1 Flow Velocity Simulation

Vectors for the velocity of groundwater flow were simulated using HTFLOW©, which employs an inversion process to match theoretical curves with the observed temperature data. When the observed temperature data are discontinuous or exceed the upper bounds of the recommended velocities, the simulation becomes unstable and difficult to converge and could result in inversion errors. In general, small, abrupt temperature changes can be simulated by varying the time-steps (averaging the data to smooth the curve).

During the study period, some flow sensors recorded huge changes in temperature gradient as a result of exposure to ground water flows in excess of the specified 2.0ft/day upper limit. These high ground water flows induce large inversion errors and an unreliable calculated velocity. In such cases, velocity data were omitted represented as corresponding data gaps in the hydrographs. For example, deep flow sensor D01 showed several gaps in velocity data during the aquifer hydraulic testing period. However, the raw millivolt data collected in these circumstances provided a useful, if qualitative, window into how quickly flow vectors changed.

4.4.2 Placement of Flow Sensors in Relation to Direction of Groundwater Flow

The flow sensors were installed based on distance from the GCW and relative to the expected natural direction of groundwater flow toward the southwest. Based on this assumption, cross gradient (southeast) and downgradient (southwest) clusters of flow sensors were installed. However, because of the probable presence of a groundwater flow divide near the GCW, direction of groundwater flow is more variable. As a result, the relationship of the flow sensors to the horizontal hydraulic gradient is most likely transient. Therefore, the flow sensors and clusters are referred to as "southeast" and "southwest," rather than "cross gradient" and "downgradient" for this evaluation.

4.4.3 Depth of Shallow Flow Sensors with Respect to Water Table

The manufacturer's recommended installation depth requires a minimum of 5 feet of saturated aquifer material between the top of the flow sensor and the water table. If the flow sensor is too near the unsaturated zone, which tends to be higher in temperature than the underlying groundwater, then the existing temperature gradient will incorrectly be interpreted by the sensor as upward flow. These superposed vectors can be accounted for and corrected using the programs' vector subtraction feature. To evaluate the flow in the upper screened interval, it was decided in the field to install the shallow sensors at a depth of approximately 1 foot below the existing groundwater surface (approximately 8 feet below ground surface) to allow the sensor to be placed at a depth similar to the upper screened interval of the GCW. The limited water column above the sensors may have impaired the sensor's performance. However, it was suspected that deeper placement of the flow sensors would compromise the ability to evaluate GCW performance in the shallow aquifer zone.

4.4.4 Accuracy and Precision of Flow Sensor Data

Past studies conducted by independent parties have shown that the flow sensors accurately record precise flow velocity data when directly compared to piezometric analysis in fluctuating flow environments such as occur in natural ground water/surface water interactions as well as pump test of many varieties. Though the probes routinely and accurately record fluctuations in flow velocities, flow velocities higher than 2 ft/day have higher interpretation errors. This upper limit is dictated by the sensor geometry and the heat flow equation central to the algorithm. The algorithm used by the sensor to calculate a flow vector requires the last collected data point; if that last data point is outside the upper specified limit, it will calculate the next data point but yield an incorrect velocity. In addition, rapid oscillations in flow velocities, as might be experienced by turning a nearby pump on and off very quickly, may yield ambiguous data. Some measure of equilibrium must be attained between changes in velocities for any one velocity to be calculated faithfully.

4.4.5 Physical Reliability of Flow Sensors

Each flow sensor consists of a rod of low thermal conductivity surrounded by a thin flex circuit heater, an array of 30 temperature thermistors, and a waterproof jacket constructed from high-density plastic and PVC. The estimated life of the flow sensors is 1 to 2 years (Ballard 1996) though many have lasted much longer.

The flow sensors are capable of measuring groundwater flow velocities in the range of approximately 5 X 10^{-6} to 1 X 10^{-3} centimeters per second (cm/s) (0.014 to 2.8 feet per day) (Ballard 1996). Higher flow rates than were anticipated near the GCW exceeded the capability of the instruments. For this evaluation, flow velocities greater than 3 feet per day were considered less reliable.

5.0 RESULTS AND INTERPRETATION OF FLOW SENSOR DATA COLLECTION

Groundwater velocity vectors were calculated from the temperature data collected from each flow sensor. When the GCW was not in operation, the measured groundwater velocity vectors were assumed to be the background velocity. These background velocity vectors for each of the shallow flow sensors were then subtracted from all of the velocity vectors using vector subtraction. This process essentially reduced the ambient groundwater flow vector to zero, primarily to observe the effects of pumping and GCW operation on the groundwater flow regime.

5.1 GCW CIRCULATION OPERATION (JULY 1 TO JULY 30, 2000)

This section describes the groundwater velocity data collected during July 2000. Data from this period are presented in Figures 12 through 26 and in Table 6. Table 7 provides a chronology of probable GCW operational events during July and August 2000, as interpreted from the flow sensor data.

5.1.1 Horizontal and Vertical Groundwater Darcy Velocities

Horizontal and vertical groundwater Darcy velocities are presented and discussed in this section.

Horizontal Darcy Velocities. Figures 12 and 13 present hydrographs of horizontal groundwater Darcy velocity versus time in the deep aquifer zone, with Figure 12 showing the actual data and Figure 13 displaying data corrected for background. The background horizontal velocities are very low, on the order of 0.01 ft/day; therefore, differences between the two sets of data are insignificant.

The flow sensor data indicate that the GCW was not operational until July 11, when the four flow sensors in the deep aquifer zone recorded sharp increases in horizontal velocities. The increases in flow velocity recorded on July 11 are caused by initiation of the long-term GCW circulation mode test; that is, simultaneously pumping from the lower screen and injecting into the upper screen. The responses of the flow sensors indicate that all of the deep sensors were in an area of the aquifer zone that was affected by operation of the GCW. Southwest flow sensor D03, farther from the GCW, exhibited a greater response to operation of the GCW than did flow sensor D02, which is closer to the well. Southeast flow sensor C02, which is closer to the GCW, exhibited a greater response to operation of the GCW than did flow sensor C04, farther from the pumping well. Different responses in southwest flow sensors D02 and D03 possibly indicate aquifer heterogeneity and anisotropy in this direction. According to the flow sensor data, the long-term GCW test ended late on July 28, 2000, resulting in a test period of about 17 days. The velocity data from the flow sensors suggest that the GCW circulation flow was generally constant over the testing period.

Flow inversion errors versus time, shown in Figure 14, indicate that inversion errors increased when the flow velocity is higher during the operation period from July 11 to July 28, 2000. Thermistor temperature data versus time shown in Figure 15 indicate that flow sensor C02 recorded substantial variations in temperatures during the GCW testing period.

Horizontal groundwater Darcy velocities in the shallow aquifer zone are shown in Figures 16 and 17; Figure 16 shows the actual measurement data, and Figure 17 displays data corrected for background. As with the deep aquifer zone, the data collected before July 11 shows the natural flow velocities, which in the shallow aquifer zone are approximately 0.3 to 0.5 ft/day. On July 11, 2000, similar to the deep flow sensors, the shallow flow sensors recorded a sharp change in horizontal Darcy groundwater velocity. Southeast flow sensor C01, which is closer to the GCW, showed lower horizontal velocities than were measured at southeast flow sensor C03, which is farther from the GCW. Horizontal velocities recorded at shallow southeast flow sensor C03 were similar to southwest flow sensor D01, on the order of 1.5 to 2 ft/day.

Flow sensor inversion errors versus time, shown in Figure 18, indicate that inversion errors increased by up to approximately 0.6 °C during the GCW testing period. The 0.6 °C inversion error is generally considered the upper limit of the errors for reasonably reliable velocity simulations. Thermistor temperatures versus time, shown in Figure 19, indicate that more variation in temperature at flow sensor C01 occurred during the GCW testing period.

The net flow velocities for the deep flow sensors ranged from 0.5 to 1.5 ft/day during the GCW testing period. The net flow velocities for the shallow flow sensors ranged from 0.5 to 2.0 ft/day during the GCW testing period.

Vertical Darcy Velocities. The measured vertical Darcy groundwater velocities versus time in the deep aquifer zone are shown in Figure 20. Figure 21 shows the vertical flow velocities with background flow removed. There is very little difference between the two sets of hydrographs, indicating that the background vertical velocities are low in comparison to the changes in flow velocity during the test period. As with the horizontal velocities, a change in the vertical velocities occurred on July 11. This change is the start of pumping associated with the long-term GCW test. The most significant change in the vertical velocity occurred in flow sensor C02, 8.9 feet southeast of the GCW, where the vertical velocity reversed from upward to downward, to approximately minus 5.0 feet per day. The change in vertical velocity was much less pronounced in the other deep southeast flow sensor, C04. At southwest flow sensors D02 and D03, the more significant change in vertical velocity occurred at D03, farther from the GCW than is flow sensor D02, which exhibited a much less pronounced response that was similar to flow sensor C04. Vertical groundwater velocities in each of the deep flow sensors appear to have stabilized quickly after the GCW test began and remained consistent until the apparent end of the test on July 28, 2000.

Vertical velocities versus time measured in the shallow aquifer zone are shown in Figures 22 and 23. One of the shallow flow sensors, southeast flow sensor D01, recorded a brief change in vertical velocity on July 8, 2000, which was not registered by other shallow flow sensors C01 and C03 or any of the deep flow sensors. The reason for this brief change in vertical flow velocity in flow sensor D01 is unknown.

5.1.2 Horizontal Groundwater Flow Directions

Horizontal directions of groundwater flow under GCW circulation mode measured in the deep aquifer zone are shown in Figure 24. The data shown were collected at 4 p.m. on July 28, 2000, near the end of the pumping period associated with the GCW testing period. It is assumed that groundwater circulation reached a steady state condition at the end of the GCW testing period.

The length of the arrows shown on Figure 24 represents the magnitude of horizontal flow velocity. It appears that velocities of groundwater flow in three out of the four sensors are on the order of 1 foot per day. Assuming natural flow velocities in the deep aquifer flow zone on the order of 0.01 ft/day, the arrows that represent vectors of velocity and direction in Figure 24 indicate that all of the flow sensors are in areas that were affected by pumping of the GCW. In general, except for flow sensor D03, the directions of groundwater flow shown are toward the lower screen of the GCW.

Figure 25 shows the horizontal Darcy velocity and direction of flow in the sensors for the shallow aquifer zone. The flow velocities at sensors C03 and D01 are an order of magnitude higher than the estimated natural rate of flow in the shallow aquifer zone of about 0.3 ft/day, with little change recorded at flow sensor C01. The directions of flow are away from the GCW, indicating that the sensors in the shallow aquifer zone were recording the effects of water recharged to the upper screen of the GCW.

5.1.3 Resultant Groundwater Flow Velocities Projected in Cross-Section

Resulting groundwater flow velocities and directions, measured by the flow sensors on July 28, 2000, were projected onto cross-section AOB, shown in Figure 26. (The location of cross-section AOB is shown in Figure 6.)

Figure 26 shows that under pumping and reinjection conditions, as represented at the end of the GCW circulation test, velocities and directions of groundwater flow in the deep and shallow aquifer zone were clearly altered by operation of the GCW. The highest velocities were recorded in sensors closest to the GCW, C01, C02, and D01. The flow regime near the GCW, as defined by those sensors, appears to contain a more pronounced component of vertical flow than of horizontal flow. This phenomenon is consistent with the Oregon Graduate Institute's model predictions and observations during aquifer testing.

The magnitude of flow velocity reflected on Figure 26 may be less reliable than the directions of the recorded flow because (1) flow velocities at sensors C01, C02, and D01 are out of the range that can be measured, according to specifications for the flow sensors, and (2) the shallow flow sensors may be significantly affected by ambient temperatures in the vadose zone. Nevertheless, flow at each of the shallow flow sensors is directed away from the GCW, while flow recorded at each of the deep flow sensors is toward the GCW, consistent with the direction expected in a circulation cell produced by operation of the GCW.

5.2 FINAL PUMP-AND-TREAT TESTING (AUGUST 1 TO AUGUST 31, 2000)

This section describes the data on velocity and direction of groundwater flow collected during the August 2000 GCW final pump-and-treat test. Data from this period are presented in Figures 27 through 41 and in Table 6. Table 7 provides a chronology of probable events during August 2000 as interpreted from the flow sensor data.

5.2.1 Horizontal and Vertical Darcy Groundwater Velocities

Horizontal Darcy Velocities. Figures 27 and 28 show hydrographs that display horizontal groundwater Darcy velocities versus time, as recorded in the deep aquifer zone during August 2000. The actual data are shown in Figure 27, while the data with background removed are shown on Figure 28. The background flow velocities are low, so there is very little difference between the two figures. The hydrographs indicate that the GCW pump-and-treat test started and stopped several times during the final pump-and-treat tests, as indicated in Table 7. The changes in horizontal velocity measured by the flow sensors are consistent between pumping events, suggesting that the pumping rate was similar during the period. In general, the horizontal velocities at the same deep sensors were lower than were recorded during the long-term GCW circulation test, suggesting that the pumping rate for the pump-and-treat test was lower.

Southeast flow sensor C02, closer to the GCW, recorded higher velocities (0.5 ft/day) during the pumping events than were recorded at southeast flow sensor C04 (0.3 ft/day), farther from the GCW. Southwest flow sensors D02 and D03 recorded similar velocities during the pumping events, on the order of 0.6 ft/day.

Figure 29 shows flow sensor inversion error versus time. A higher inversion error is associated with flow sensors C02 and D02. The large inversion error is probably caused by abrupt changes in flow velocity associated with the beginning and end of pumping. However, the inversion error is within the acceptable limit of 0.6 °C.

Figure 30 shows thermistor temperature versus time for each of the flow sensors in the deep aquifer zone. The data show that the largest variation in temperatures among different thermistors was associated with flow sensor C04.

Hydrographs of horizontal Darcy groundwater velocities versus time in the shallow aquifer zone during August 2000 are shown in Figures 31 and 32. Figure 31 shows the actual data, and Figure 32 shows the data with background removed. Comparison of the hydrographs shown in Figure 31 and Figure 32 indicates that the background flow measured by flow sensors in the shallow aquifer zone is much higher than in the deep aquifer zone.

The background velocity of flow indicated by the shallow flow sensors is likely artificial because the shallow flow sensors were installed too near to the water table, and the measurements were altered by the ambient temperature in the vadose zone. The hydrographs displayed in Figure 32 show that the sensors in the shallow zone were recording events associated with the final pump-and-treat test. These events are the same as those recorded by the flow sensors in the deep aquifer zone. Therefore, the data for the shallow sensors can be used qualitatively to evaluate changes in flow pattern caused by pump-and-treat operations, even though the absolute velocity values recorded by the shallow flow sensors remain questionable.

Inversion errors associated with the shallow flow sensors are shown in Figure 33. In general, inversion errors in the shallow flow sensors were on the order of 0.2 to 0.3 ºC in August 2000, which is within the acceptable range.

Thermistor temperature (in ºC) versus time for the flow sensors in the shallow aquifer zone is shown in Figure 34. Thermistor temperatures in all three of the shallow flow sensors show that the temperature distribution of the thermistors is stable.

Vertical Darcy Velocities. Figures 35 and 36 show hydrographs of vertical Darcy groundwater velocities versus time in the deep aquifer zone; Figure 35 shows the actual data, and Figure 36 shows the data with background removed. The differences between the two sets of hydrographs are slight because the background flow velocities in the deep aquifer zone are low. The vertical velocities in the deep aquifer zone (Figure 36) indicate that vertical flow caused by pump-and-treat operation is clearly shown in southeast sensor C02. However, the response to pumping is limited at other flow sensors, particularly D02 and C04. These velocity data indicate that significant vertical recharge may occur near the GCW in the southeast direction when the deep aquifer zone is pumped. The vertical recharge was not measured in other directions.

Figure 37 shows measured velocity data, and Figure 38 shows data with background velocity removed. The apparent background velocities are an artifact of the temperature gradient imparted from the warmer unsaturated zone sediments slightly above the top of the shallow sensors. Subtracting out the background vector essentially negates the unsaturated zone temperature differential that appears like an enhanced vertical flow velocity. Nevertheless, data for the shallow flow sensors did respond to the events of the pump-and-treat testing. The most significant response was recorded in southwest flow sensor D01. Of the two southeast flow sensors, the more pronounced response was recorded at flow sensor C03, which is farther from the pumping well. This phenomenon may reflect aquifer heterogeneity and anisotropy.

5.2.2 Horizontal Directions of Groundwater Flow

Horizontal directions of groundwater flow recorded in the deep aquifer zone near the end of the pump-and-treat test are shown in Figure 39. The data shown were collected at 6 p.m. on August 25, 2000, near the end of a pumping period that began on the morning of August 21, 2000. It was one of several distinct pumping events associated with the final pump-and-treat test.

This time was selected to represent a steady-state flow condition under the pump-and-treat operation. Velocity of groundwater flow recorded by three of the four sensors is on the order of 0.5 to 1 foot per day. Assuming natural velocities of flow in the deep aquifer flow zone on the order of 0.01 ft/day, the arrows that show velocity and direction in Figure 39 indicate that all of the flow sensors in the deep aquifer zone are affected by pumping of the GCW. In general, the flow directions measured by the sensors are toward the GCW. Deviations in the southwest direction may reflect aquifer anistotropy and preferential groundwater flow paths.

Figure 40 shows the horizontal direction of flow in the shallow aquifer zone measured by the sensors. The velocities at the three flow sensors are similar to the estimated natural rate of flow in the shallow aquifer zone of about 0.3 ft/day, suggesting that pumping in the deep aquifer zone had limited impact on the flow pattern in the shallow groundwater.

5.2.3 Resultant Groundwater Flow Velocities Projected in Cross-Section

Groundwater flow velocities and directions recorded on August 25, 2000, were projected onto cross-section AOB, as shown in Figure 41. (The location of cross-section AOB is shown in Figure 6.) A vector calculation and vector component projection approach was used to generate Figure 41.

Under conditions represented at the end of the final pump-and-treat test, velocities and directions of flow measured by the sensors in the deep and shallow aquifer zones show a radial flow pattern toward the pumping interval in both the deep and shallow aquifer zones. The flow regime as defined by all of the sensors is consistent with the pattern expected by pumping the lower screened interval of the GCW. Figure 41 shows that the flow sensors are capable of measuring and defining patterns of flow in groundwater around the GCW or a pumping well.

5.3 AQUIFER HYDRAULIC TESTING (SEPTEMBER 13 TO SEPTEMBER 19, 2000)

Flow sensor data from the seven sensors were collected during aquifer hydraulic testing conducted from September 13 through September 19, 2000. The following section describes and interprets the data collected during this period.

Data collected during the aquifer hydraulic testing period are in 2-minute intervals instead of a 30-minute interval. The purpose for the high frequency of data collection is two fold: (1) pumping or dipole operation is better controlled in terms of discharge rate and pumping duration; therefore, flow sensor data can be interpreted with more certainty on GCW operation, and (2) aquifer testing events can be short and transient conditions recorded by flow sensors. This latter factor is important for data interpretation.

Multiple aquifer hydraulic tests were conducted to mimic GCW operations. The effect of the long-term constant discharge test on groundwater flow patterns was equal to the pump-and-treat operation. DFTs were conducted to mimic GCW operation in circulation mode. The frequent collection of data from the flow sensors was intended to collect detailed measurements on the flow regime near the GCW.

5.3.1 Horizontal and Vertical Darcy Groundwater Velocities

Horizontal Darcy Velocities in Deep Aquifer Zone. Figures 42 and 43 are graphs of horizontal groundwater Darcy velocity versus time as measured in the deep aquifer zone during the aquifer testing period from September 13 through 19, 2000. Figure 42 shows original or uncorrected data, and Figure 43 shows data corrected for background and irregularities.

Irregularities in data from the flow sensors were observed during the aquifer hydraulic testing period, which were probably caused by changing directions or velocities in flow within a short period (multiple tests conducted in a few days) and more frequent data collection (2 minutes instead of 30 minutes). The irregularities were corrected by the enlarged time-averaging window for simulation of flow velocity. This technique allows for “smoothing” the velocity curves to eliminate abrupt irregularities.

The hydrographs in Figures 42 and 43 indicate that the flow sensors in the deep aquifer zone recorded increases in the horizontal flow velocity in response to each of the aquifer tests. Figures 42 and 43 suggest that each of the flow sensors was collecting data consistently during different aquifer testing events, as demonstrated by similarities in the shapes of the curves recorded, particularly at the beginning of each event. Maximum velocities recorded in the sensors during the fourth phase of the step testing, when the pumping rate was 15 gpm, were in all cases lower than the velocities recorded during a comparable interval at the start of the constant rate pumping test, when the pumping rate was 10 gpm. These lower velocities probably are the result of the short duration of the step test, so that a steady-state flow regime was not developed.

During the constant rate pumping test, the horizontal velocities stabilized in all of the flow sensors in the deep aquifer zone after approximately 10 hours of pumping. After that time, the horizontal velocities measured in each of the flow sensors remained stable until the end of the test. Maximum, stabilized velocities were similar to and in most cases slightly higher than the maximum horizontal velocities recorded during the last step test.

Southeast flow sensors C02 and C04 responded predictably to pumping, with the sensor closest to the GCW (C02) consistently showing a higher horizontal velocity than was recorded at sensor C04, the sensor farther from the GCW. However, southwest flow sensors D02 and D03 showed responses to pumping the GCW that are the reverse of the response expected. During the constant rate pumping test, the greater horizontal velocity was recorded at sensor D03, which is farther from the GCW than is sensor D02. It is not known why the flow sensors in D02 and D03 did not respond to the pumping of the GCW as expected. However, it is possible that the flow sensors recorded abnormal aquifer responses to GCW pumping. Flow sensor D03 is located adjacent to piezometer 3PZD, where slow initial drawdown responses, excessive maximum drawdown, and nonequilibrium conditions were noted in response to pumping at the GCW during aquifer testing. These factors suggest that aquifer heterogeneity and anisotropy are probably more pronounced in southwest of the GCW.

Figure 44 shows inversion error, expressed as ºC versus time, in the flow sensors in the deep aquifer zone. Figure 44 indicates that higher inversion errors are associated with flow sensors closest to the GCW, C02 and D02. In addition, the inversion error seemed to increase with increases in magnitude of flow velocity at each flow sensor. Figure 45 plots thermistor temperature versus time in flow sensors in the deep aquifer zone.

Horizontal Darcy Velocities in Shallow Aquifer Zone. Figures 46 and 47 show horizontal flow velocities measured in the shallow aquifer zone during aquifer testing. The hydrographs indicate that the changes in velocity in the shallow aquifer zone recorded are significantly less than were recorded in sensors in the deep aquifer zone. The overall pumping events are identifiable. However, the magnitude of the change in velocity recorded by the shallow flow sensors is not reliable.

The horizontal velocities measured at the shallow flow sensors during dipole testing, particularly during Dipole Tests 6 and 7, are shown in Figures 46 and 47. The velocities shown in these figures would be expected during dipole testing because the shallow aquifer zone was being recharged through the upper-screened interval of the GCW. The velocity measured at southeast flow sensor C03, farther from the GCW, was consistently higher than was indicated at sensor C01, which is closer to the GCW. Southwest flow sensor D01 exhibited a response that was slightly more pronounced than at southeast flow sensor C01; both are installed approximately the same distance from the GCW, at 7.6 feet and 7.7 feet. Graphs shown in Figure 48 suggest that large inversion errors were observed during data manipulation for sensors C01 and D01, which are closer to the GCW. During Dipole Tests 6 and 7, the errors exceeded 0.6 °C. Therefore, the calculated change in flow velocity is not considered accurate. Figure 49 plots thermistor temperature versus time in the flow sensors in the shallow aquifer zone. The figure shows that temperature plots from different thermistors revealed a cross pattern during dipole tests instead of a parallel pattern, which makes the simulation of inversion more difficult and unstable and may account for the high inversion error.

Vertical Darcy Velocities in Deep Aquifer Zone. Figures 50 and 51 are hydrographs of the vertical groundwater Darcy velocity versus time as measured by the deep flow sensors during aquifer testing. Figure 50 shows the original or uncorrected data; Figure 51 shows data corrected for background and irregularities. The hydrographs indicate that the flow sensors in the deep aquifer zone recorded vertical changes in flow velocity in response to each of the aquifer tests; however, the response was much less significant in comparison to the horizontal flow velocity. Changes in vertical velocity were most pronounced at flow sensor C02, 8.9 feet from the GCW, where negative vertical velocities indicate induced, downward vertical flow. Negative, or downward, vertical velocities were also noted at flow sensor D03.

Similar to the horizontal velocity data, flow sensor D02, closest to the pumping well, recorded a lower vertical velocity than was recorded at sensor D03, farther from the GCW. Also similar to the horizontal velocity data, flow sensors C02 and C04 indicate that the vertical component of velocity recorded is consistently greater at sensor C02, which is closest to the pumping well.

Vertical Darcy Velocities in Shallow Aquifer Zone. Figures 52 and 53 show vertical groundwater Darcy velocities versus time in the shallow aquifer zone. The hydrographs shows that data from the shallow sensors can be used to qualitatively identify Dipole Tests 6 and 7 events. The change in vertical flow velocity in the shallow flow sensors are not clearly pronounced.

5.3.2 Horizontal Directions of Groundwater Flow

Natural Flow Conditions, September 18, 2000. Figures 54 and 55 show horizontal directions of groundwater flow recorded by the sensors measured under natural flow conditions in the deep and shallow aquifer zones. These figures display data collected on September 18, 2000, at the end of the recovery period after the constant-rate pumping test. The results of the calculation of flow vectors are also presented in Table 6.

In the deep aquifer zone (Figure 54), all four sensors indicate horizontal flow velocities are very low, generally less than 0.05 ft/day. In general, flow sensors indicate groundwater flow to the northeast, while data for western-most sensor D03 deviated slightly to the northwest. The northwestern direction of groundwater flow measured by the flow sensors is generally supported by groundwater elevation data collected using In Situ miniTROLL® transducers in piezometers completed in the deep aquifer zone for the same period. The groundwater elevation data are also shown on Figure 54.

The flow sensors in the shallow aquifer zone indicate that the direction of groundwater flow in the shallow aquifer zone is similar to the deep aquifer zone, measured in all three flow sensors. This direction of flow is consistent with water levels measured in the shallow piezometers during the same period. The magnitude of the Darcy velocity in the shallow groundwater is much higher than the velocities in the deep aquifer zone (Figure 55). The velocities in the shallow aquifer zone at different sensor locations are similar, approximately 0.5 ft/day.

The groundwater Darcy velocity measured by the shallow flow sensors, which was one order of magnitude higher than for the deep aquifer, may not represent the actual, natural flow conditions in the shallow aquifer zone. The data for the shallow sensors were considered unreliable for quantitatively interpreting the magnitude of velocity because of the large temperature distribution of the thermistors, possibly affected by ambient temperatures in the vadose zone. The data, however, are useful for qualitatively interpreting directions of groundwater flow, which can supplement water level data collected from the piezometers.

Constant Rate Pumping Test, September 16, 2000. Data collected near the end of the constant rate pumping test are considered to represent a steady-state flow regime around the GCW under pumping conditions. The pumped interval was the lower screen of the GCW in the deep aquifer zone. Figures 56 and 57 show horizontal groundwater Darcy velocity vectors, collected on September 16, 2000, at the end of the constant rate pumping test.

Flow vectors shown on Figure 56 were calculated based on data with background removed; therefore, the vectors represent the "net effect" or changes caused by pumping the deep aquifer zone. Figure 56 shows that flow velocities are most significant at southwest flow sensor D03. In general, horizontal directions of groundwater flow in the four deep flow sensors are toward the GCW, consistent with the flow pattern expected during pumping. Deviations in directions of flow were observed at flow sensor D03, which is likely caused by aquifer anisotropy and preferential pathways that may exist near the GCW.

Figure 57 shows that the net effect of pumping on the flow velocity in the shallow aquifer zone is generally less than in the deep aquifer zone. In the southeast direction, sensors C01 and C03 both measured horizontal flow that shifted in the direction of the GCW. According to Table 6, the vertical velocities all changed from upward to downward, which suggests influence by pumping the lower screened interval of the GCW. The change in horizontal flow velocities under pumping conditions is much less pronounced in the shallow flow sensors than in the deep flow sensors. This response would be expected because pumping occurred in the deep aquifer zone.

Dipole Flow Testing, September 18, 2000. Figures 58 through 61 show horizontal groundwater Darcy velocities in the deep and shallow aquifer zones as measured during the two dipole tests. Figures 58 and 59 show horizontal vectors for groundwater flow (Darcy velocities) calculated at the end of Dipole Test 6. Figures 60 and 61 show horizontal vectors for groundwater flow calculated at the end of Dipole Test 7, which was also conducted on September 18, 2000.

As shown in Figure 58, the horizontal directions of flow recorded by each of the sensors in the deep aquifer zone are similar to pumping conditions at the end of the constant rate pumping test (Figure 56). Velocities of flow, however, were smaller at the end of Dipole Test 6, which could be due to the shorter duration of Dipole Test 6 or could suggest that velocities of groundwater flow in the deep aquifer zone were affected by water injected into the upper screened portion of the GCW during dipole testing. The directions of horizontal flow in the deep aquifer zone recorded during Dipole Test 6 are nearly identical to the directions recorded during the pumping test. The similarities in velocities and directions of horizontal flow between the pumping and dipole tests in the deep aquifer flow zone suggest that patterns of flow in the deep aquifer zone are similar during pumping of the lower screened interval and circulation created by the GCW.

As shown in Figure 59, velocities and directions of horizontal flow measured by the three sensors in the shallow aquifer zone are to the southeast and southwest, away from the GCW. These data suggest that the flow sensors are recording responses in the shallow aquifer zone to water injected into the GCW.

Directions and velocities of flow measured in the deep aquifer zones shown in Figure 60 at the end of Dipole Test 7 are similar to the end of Dipole Test 6 (Figure 58), except that the magnitude of velocities recorded during Dipole Test 7 are slightly higher than were recorded during Dipole Test 6. This difference would be expected since Dipole Test 7, although conducted at the same pumping rate, was of longer duration. Similarly, as shown in Figure 61, directions and velocities of flow measured by sensors in the shallow aquifer zone at the end of Dipole Test 7 are similar to the end of Dipole Test 6 (Figure 59).

The horizontal flow vectors shown in Figure 58 through 61 clearly indicate that a radial flow pattern was observed in both the shallow and deep aquifer zones. The flow converges toward the GCW in the deep aquifer zone and diverges from the GCW in the shallow aquifer zone. Conclusions from the evaluation of data collected from the flow sensors during the dipole tests can be summarized as follows:

- The patterns in groundwater flow measured by the sensors is consistent with the flow pattern defined by water levels in the piezometers and simulated by flow models.
- Under pumping and reinjection conditions of Dipole Tests 6 and 7 (pumping and injection rate of 12.5 gpm), all of the flow sensors recorded identifiable changes in flow velocities (magnitude and direction).
- A circulation cell can be measured and defined by flow sensors that are appropriately placed around the GCW.
- Net flow velocity changes can be reasonably calculated by removing the “background,” which may represent the impact or “noise” of natural flow for the shallow flow sensors.

5.3.3 Resultant Velocities of Groundwater Flow Projected in Cross-Section

Groundwater flow velocities were calculated and projected onto cross-section AOB. Figures 62 through 65 show the vertical patterns in groundwater flow under natural flow conditions, pumping conditions, and two dipole test conditions. The location of cross-section AOB is shown in Figure 6.

Under natural flow conditions, as represented by the end of the recovery period of the constant-rate pumping test (Figure 62 and Table 6), the deep flow sensors recorded very low vertical flow. Even though three of the four deep flow sensors recorded an upward flow, the magnitude was so small that the error could be large, yielding misleading calculated flow directions. A stronger upward flow component appears in the shallow aquifer zone indicated by the shallow sensors. However, the upward flow recorded by the shallow flow sensors are most likely caused by the impacts of temperature in the vadose zone because the shallow flow sensors were installed too near to the water table; the temperature gradient is interpreted by the software as an upward flow.

Figure 63 shows the flow vectors projected onto cross-section AOB. The vectors represent the net flow changes under pumping conditions, that is, the background was subtracted from the actual flow measurements. As shown in Figure 63, the directions of flow in both the deep and shallow aquifer zones are toward the lower screen of the GCW, the pumping interval used during the test. This flow pattern is consistent with the transducer measurements from the piezometers, and are expected because there is no aquitard between the shallow and deep aquifer zones.

Data from flow sensors D03 and C02 show a stronger vertical component of flow than of horizontal (Figure 63). This differential could be the result of strong vertical recharge from the shallow aquifer zone to the pumped interval at these two locations. The horizontal component of flow measured by the two flow sensors, however, is generally consistent with data for the other two flow sensors.

Figures 64 and 65 show groundwater flow vectors projected onto cross-section AOB during dipole testing (Dipole Tests 6 and 7). In general, the velocities of flow in the deep aquifer zone during dipole testing, shown as flow vectors, were similar to velocities during pumping conditions (Figure 63). The patterns in the shallow aquifer zone, however, reflect dramatic outward flow components from the GCW. The outward and downward flow regime is consistent with the effects of recharge to the upper screen.

Velocities and directions of groundwater flow measured by the sensors during Dipole Test 6 and 7, (Figures 64 and 65) appear to clearly define a three-dimensional circulation cell of the GCW. Water injected in the upper screen of the GCW causes flow in the shallow aquifer zone to move away from the GCW, while pumping the lower screen of the GCW induces flow toward the GCW.

5.4 POST-TESTING PERIOD (SEPTEMBER 20, 2000 TO APRIL 1, 2001)

This section discusses data collected from the flow sensors during the post-testing period, from September 20, 2000 to April 1, 2001, when the GCW was not in operation.

5.4.1 Horizontal and Vertical Groundwater Darcy Velocities

Figures 66 through 76 and Table 6 provide velocities and directions of groundwater flow for data that represent the natural regime during the post-test period from September 20, 2000, through April 1, 2001. The GCW was not in operation during this time, and groundwater flow recorded by the sensors is likely to represent natural conditions. Shallow flow sensor D01 malfunctioned during this period. Therefore, no velocity data was calculated for sensor D01.

Horizontal Darcy Velocities. Figure 66 shows horizontal groundwater Darcy velocity versus time in the deep aquifer zone measured by the flow sensors. All the flow sensors in the deep aquifer zone recorded very low horizontal velocities, between 0 and 0.1 ft/day, during the period. On February 1, 2001, the horizontal flow velocity at sensor C04 in the deep aquifer zone shows a steady increase until the end of the measurement period on April 1, 2001. None of the other deep flow sensors recorded a corresponding increase. Inversion error calculated for the flow sensors (Figure 67) indicates that it also increased during the same period. According to HydroTechnics, the increase in flow velocity recorded at flow sensor C04 during the beginning of February 2001 is caused by drift in the thermistor temperature for unknown reasons. The data collected after early February 2001 from sensor C04 were deleted because HydroTechnics considered them unreliable.

Data from flow sensor D03 (Figures 66 through 68) also show several gaps during this period. Data gaps were caused temperature data that exhibited electrical "noise" were deleted. It is unknown how the electrical noise was introduced.

Horizontal Darcy velocity versus time in the shallow aquifer zone is shown in Figure 69. Data from flow sensors C01 and C04 indicate fluctuations on the order of 0.1 to 0.4 ft/day in horizontal Darcy velocity during this period. Inversion errors for flow sensor data from the shallow aquifer zone (Figure 70) indicate stable error during the measurement period. Temperatures measured by the thermistors are shown in Figure 71. The velocity measured by the shallow flow sensors were not considered reliable because of impacts from temperature in the vadose zone.

Vertical Darcy Velocities. Vertical groundwater Darcy velocities measured in the deep aquifer flow zone (Figure 72) shows a similar trend to the horizontal velocities in Figure 66. They are low and stable throughout the period, with the exception of data measured at flow sensor C04, which show an increase beginning on approximately February 1, 2001.

Darcy velocities measured in the shallow aquifer flow zone (Figure 73) show that the vertical velocity recorded at flow sensor C01 was approximately 1.0 ft/day and decreased with time. However, the vertical velocity at flow sensor C03 fluctuated between 1.0 and 3.0 ft/day in later 2000 but stabilized in early 2001 at 1.5 ft/day.

5.4.2 Horizontal Groundwater Flow Directions

Figures 74 and 75 show the horizontal groundwater velocity vector for the deep and shallow aquifer zones. The velocities and directions shown in Figure 74 for the deep aquifer zone flow generally to the east in the southeast flow sensors (C02 and C04) and generally to the west in the southwest flow sensors (D02 and D03), indicating a possible groundwater flow divide. The directions of flow shown in Figure 75 for the shallow aquifer zone indicate generally eastward flow away from the GCW, consistent with data for deep sensors C02 and C04. However, the direction of flow interpreted from data is not considered highly reliable because the natural flow gradient is small at the site. The error caused by noise could be added to the velocity data and alter the interpreted direction of flow.

5.4.3 Resultant Groundwater Flow Directions Projected in Cross-Section

Figure 76 shows groundwater flow vectors projected onto cross-section AOB during the post-testing period when the GCW was not in operation. In this diagram, the vertical direction of groundwater flow in five of the six sensors is upward. The high flow velocity in the shallow zone is believed to be the effects of ambient temperatures in the vadose zone. Because the magnitudes of the flow vectors are small, the directions of flow indicated in Figure 76 can be considered a random distribution.

6.0 RESULTS OF TECHNOLOGY EVALUATION

This section presents the results of the SITE demonstration of the HydroTechnics flow sensors at the CCAS site in Florida. The results are presented by and interpreted in relation to each project objective. Each primary and secondary project objective is listed and followed by a discussion of the results in relation to the objective.

6.1 PRIMARY OBJECTIVE

This subsection discusses the results associated with the primary project objective. Primary objectives are considered critical for the evaluation of the technology. For this evaluation, one primary objective was established:

P1 Evaluate the flow sensor's ability to detect the horizontal extent of the GCW groundwater circulation cell based on a change in the groundwater velocity criterion of 0.1 foot per day (0.03 meter per day)

This objective was achieved by measuring the changes in groundwater velocity and flow direction in seven in situ groundwater flow sensors before and during operation of GCW in recirculation mode. To analyze the data, plots of the groundwater velocity versus time were constructed for each sensor; analytical methods were not used to evaluate the data because the data plots exhibited clear trends in the change of groundwater flow velocity during operation of the GCW. For this evaluation, flow sensors that exhibited a change in velocity of equal to or greater than 0.1 ft/day from background conditions were considered to be within the horizontal extent of the groundwater circulation cell established by the GCW.

Results of the groundwater flow velocity and direction measurements collected from the seven in situ groundwater flow sensors before and during GCW operation are presented in Figures 12 through 26. These figures present both horizontal and vertical velocity measurements plotted versus time for the shallow sensors (C01, C03, and D01) and deep sensors (C02, C04, D02, and D03). Figures 12 through 23 include plots of both actual groundwater velocity data and normalized groundwater velocity data with background conditions removed.

Based on review of the horizontal and vertical velocity data with background velocities removed, groundwater velocities in all seven sensors were greater than 0.1 ft/day, indicating that all seven sensors were within the circulation cell established by the GCW, and that the horizontal extent of groundwater circulation is greater than 15 feet. Furthermore, the groundwater flow direction data suggest that groundwater in the upper portion of the treatment zone flows radially away from the GCW and that groundwater in the bottom of the treatment zone flows radially towards the GCW. This flow direction data further supports the establishment of a circulation cell, and that all the flow sensors are within the horizontal extent of groundwater circulation cell.

6.2 SECONDARY OBJECTIVES

Secondary objectives provide additional information that is useful, but not critical. Four secondary objectives were selected for the evaluation of the technology. The results associated with each of the secondary objective are presented in the following subsections.

6.2.1 Secondary Objective S1

S1 Evaluate the reproducibility of the groundwater velocity sensor data

The reproducibility of the flow sensor measurements was evaluated to provide additional information on the quality and usability of the sensor data. The reproducibility of velocity measurements was evaluated by comparing sequential groundwater flow velocity measurements at steady state conditions. During the evaluation, measurements were collected sequentially, 30 minutes apart. The periods that were selected for evaluating data reproducibility were when the groundwater velocity appeared to be in steady-state condition with minimal changes due to well operation, rain, barometric pressure, tidal influences. Since the response time of the sensors is less than 1 minute, each groundwater flow velocity measurement is independent; therefore, flow sensor reproducibility was estimated as the relative percent difference (RPD) of two sequential measurements of groundwater flow at 30-minute intervals. For each sensor, an average RPD was calculated for the horizontal and vertical velocities for each of the four operational modes. The average RPD for each sensor was determined using all sequential measurements collected during steady state conditions for each operational period.

A summary of the average RPDs for each flow sensor for each of the four GCW operational modes is presented in Table 8. No QA objectives have been established for quantitative analysis of sensor data; for this study; however, a QA objective of 30 percent for RPD was used.

Each sensor's reproducibility during the four operational periods ranged from 0.1 to 23 percent with an average of 1.9 percent and a standard deviation of 3.8. These results indicate that the reproducibility of the sensors meets the QA objective and that the data are considered acceptable for qualitative analysis. The accuracy of the sensors was not evaluated during the demonstration and the usability of the data for quantitative analysis is unknown.

6.2.2 Secondary Objective S2

S2 Evaluate the three-dimensional groundwater flow surrounding the GCW

This objective was achieved by measuring groundwater velocity and flow direction in the seven in situ groundwater flow sensors during each of the four operating periods. To analyze the data, plots of the groundwater velocity versus time were constructed for each sensor to provide an understanding of the overall changes in groundwater flow direction and velocity attributed to operation of the GCW.

Results of the groundwater flow velocity measurements collected during the four operating periods are presented in Figures 12 through 76 and are discussed below. These figures present both horizontal and vertical velocity measurements plotted versus time for all seven sensors as well as graphs of groundwater flow direction.

Long-Term GCW Operation

Based on the flow direction data collected during GCW operation, groundwater in the upper portion of the treatment zone flows radially away from the GCW, and groundwater in the bottom of the treatment zone flows radially towards the GCW. Additionally, the sensors exhibited a strong vertical flow component towards the lower screen interval (extraction zone). This flow regime suggests that groundwater circulation was occurring around the GCW.

During operation of the GCW in circulation mode, the flow sensors recorded an immediate increase in horizontal and vertical velocities when operation of the GCW was initiated. Likewise, the sensors exhibited an immediate decrease in horizontal and vertical groundwater flow velocities when operation of the GCW was terminated. The data suggest that the flow sensors are responsive to changes in groundwater flow conditions and can be used to help define and evaluate the three-dimensional flow pattern created by and surrounding the GCW. The immediate response of the sensors to changes in GCW operation suggest that the groundwater circulation cell is established almost immediately (within hours instead of days). Additionally, the velocity data from the flow sensors suggest that the GCW circulation flow was generally constant over the operating period. The magnitude and direction of groundwater flow measured at each sensor varied, with velocities ranging from 0.5 to more than 2.0 ft/day.

Final Pump-and-Treat Operation. Under conditions represented at the end of the final pump-and-treat test, velocities and directions of flow measured in the deep and shallow aquifer zones show a radial flow pattern toward the pumping interval in both the deep and shallow aquifer zones. The flow regime as defined by all of the sensors is consistent with the pattern expected by pumping the lower screened interval of the GCW.

During the final pump-and-treat operation period, the flow sensors recorded changes in flow velocity of 0.1 to more than 2.0 ft/day. As during the long-term GCW operation, the flow sensors recorded immediate increases and decreases in flow velocity, which coincided with changes in operational activities (pumping starts and stops). The changes in horizontal velocity measured by the flow sensors are consistent between pumping events, suggesting that the pumping rate was similar during the operational period. Based on the sensor data, the flow sensors appear capable of measuring and defining patterns of flow in groundwater around a pumping well.

Aquifer Hydraulic Test Operation. During the aquifer hydraulic test operation, sensor data were collected to coincide with the two aquifer tests: constant-rate discharge test and DFT. Sensor data collected during the constant-rate pumping test were consistent with the data from the final pump-and-treat operation mode, indicating a strong inward flow in the deep aquifer zone and significant vertical recharge from the upper aquifer zone. The data collected during the DFTs were consistent with data from the long-term GCW operational mode, indicating the establishment of a circulation cell. In addition, the pattern of groundwater flow is consistent with the flow pattern defined by water levels in the piezometers and simulated by flow models.

Post-GCW Operation. Post operational data were collected from the sensors to evaluate natural groundwater flow conditions near the GCW. Shallow flow sensor D01 malfunctioned during this period; therefore, no velocity data were recorded for sensor D01. All the flow sensors in the deep aquifer zone recorded very low horizontal velocities, between 0 and 0.1 ft/day, during the period. Horizontal velocities in the shallow aquifer zone indicate fluctuations on the order of 0.1 to 0.4 ft/day. However, the shallow velocity measurements are not considered reliable because of impacts form temperature variations caused by the vadose zone.

Groundwater in the deep aquifer zone flows generally to the east at the locations of the southeast flow sensors (C02 and C04) and generally to the west at the locations of the southwest flow sensors (D02 and D03), indicating a possible groundwater flow divide. In the shallow aquifer zone, groundwater flows generally toward the east, consistent with data for deep sensors C02 and C04. However, the directions of flow interpreted from the data are not considered highly reliable because the natural flow gradient at the site is small. The error caused by instrument noise could be added to the velocity data and alter the interpreted direction of flow.

In summary, the evaluation indicates that the flow sensors can be used to define and evaluate the three-dimensional flow pattern created by and surrounding the GCW. Flow velocity vector, including horizontal and vertical flow components, can be derived from the thermister temperature data provided by the flow sensors.

To more fully evaluate the three-dimensional flow surrounding a GCW, it would have been useful to install additional sensors at varying distances and depths from the GCW. A more comprehensive assessment of the groundwater flow regime could have been completed if flow sensors were installed at upgradient, downgradient, and cross-gradient locations at a minimum of three different distances from the GCW. Additionally, installing flow sensors at three different depths corresponding to shallow and deep GCW screens, as well as midway between the two screens, would have provided useful data in characterizing the groundwater flow pattern created by the GCW.

The manufacturer recommends installing the flow sensors with 5 feet (1.5 meters) of submergence because the shallow groundwater will heat up during the day, creating a thermal gradient that the sensor interprets as water flow. The shallow sensors at this site were installed with less than 5 feet of submergence because preliminary modeling results indicated that there would not be significant flow deeper than 3 feet (1 meter) into the formation. The data from the shallow sensors were successfully corrected by subtracting the background temperature gradient.

The manufacturer also recommends allowing the sensors to come to thermal equilibrium for at least 7 days before meaningful readings can be obtained. Short-term aquifer tests result in large but short-term changes in groundwater flow that were successfully interpreted with significant effort in data manipulation.

The manufacturer claims that the flow sensors measure the flow in the 3.3 cubic feet (1 cubic meter) immediately surrounding the sensor and are subject to local heterogeneities. Therefore, complex site hydrogeological conditions may require a large number of flow sensors to adequately define the circulation cell and characterize flow patterns.

The number of flow sensors installed during this study was limited by budgetary constraints. The purchase cost of a single flow sensor was $2,500. The total cost for the sensors, sensor analysis for a period of 1 year, and drilling installation was $70,000 for this project. Costs at other sites may vary depending on installation depth and subsurface conditions.

6.2.3 Secondary Objective S3

S3 Document the operating parameters of the GCW

The following operating parameters were documented for each of four system operational modes: well pumping rate, duration of system operation, and well shutdowns. A summary of operating parameters is presented below.

During the long-term operational mode, the GCW operated in circulation mode for a 17-day period from July 10 through 28, 2001. During this period, the GCW was operated at an estimated 4 gpm. Pumping stopped briefly for a 2-hour period on July 14 for mechanical repairs. A summary of the operational record is provided as Table 7.

During the final pump-and-treat operational mode, the GCW operated in pumping mode for a 27-day period from August 2 through 29, 2000. During this period, the GCW was operated at an estimated 4 gpm. Pumping stopped more than seven times during this operational mode for mechanical repairs on the wastewater treatment system. A summary of the operational record is provided as Table 7.

During the aquifer hydraulic test operational mode, the GCW was operated in both pumping and circulation modes for selected intervals from September 13 through 19, 2000. A summary of the operational record and pumping rates is presented in Appendix A, the Hydrogeologic Investigation Report. After the aquifer tests in September 2000, the GCW was not operated and the flow sensors monitored natural conditions.

6.2.4 Secondary Objective S4

S4 Document the hydrogeologic characteristics at the demonstration site

This objective was achieved by conducting a series of aquifer tests at the demonstration site from September 13 through 19, 2000, to obtain information on hydraulic communication between various zones of the aquifer beneath the site, as well as data for estimating values of aquifer hydraulic parameters such as hydraulic conductivity, transmissivity, storativity, specific yield, and anisotropy. Aquifer testing was conducted using the GCW as the pumping and injection well. Eight observation wells were used to monitor pressure changes in the aquifer. An inflatable packer was used to isolate the two screened intervals within the GCW to allow pumping from each screened interval separately. Multiple step draw-down tests, a constant rate pumping test, and seven DFTs were conducted. Appendix A, the Hydrogeological Investigation Report, provides a description of the methods and procedures and summarizes the interpretation of data from the aquifer tests and site hydrogeologic characteristics.

In summary, the conductivity of the aquifer at the Facility 1381 site decreased with depth. Based on aquifer hydraulic test data evaluation, the hydraulic conductivity ranges from 43 to 53 ft/day (1.5×10^{-4} to 1.9×10^{-4} cm/s) for the shallow (upper 7 feet or 2.1 meters) and 5 to 10 ft/day (1.8×10^{-5} to 3.5×10^{-5} cm/s) for the lower zone (7 to 25 feet or 7.6 meters); storativity of the lower aquifer zone ranges from 0.006 to 0.007; specific yield ranges from 0.06 to 0.09. The average anisotropic ratio (that is, the ratio of horizontal to vertical hydraulic conductivity) is 2.4, based on steady-state dipole flow test interpretation. Natural groundwater flow velocities at Facility 1381 are very low, ranging from 0.03 to 0.21 ft/day (0.009 to 0.064 meters per day).

The upper portion of the aquifer zone tested (shallow aquifer zone) is at least one to two orders of magnitude more permeable than the pumping interval for the deep aquifer zone. This difference complicates interpretation of data for the aquifer tests because the pumped zone is less transmissive than the unpumped zone (leaky aquifer). Significant vertical flow invalidates many two-dimensional analytical models for aquifer tests. It is believed that the hydraulic parameters calculated using the aquifer test data may be overestimated. The best estimate of properties of the aquifer should be evaluated using a combination of data from lithologic sample tests, aquifer tests, flow velocity measurements, and groundwater flow modeling.

7.0 CONCLUSIONS

The conclusions of the technology evaluation, as they relate to the demonstration project objectives, include:

Primary Conclusions

P1 Evaluate the flow sensor's ability to detect the horizontal extent of the GCW groundwater circulation cell based on a change in the groundwater velocity criterion of 0.1 foot per day (0.03 meter per day)

- During the GCW circulation operation mode, the groundwater velocities measured by all seven sensors increased by more than 0.1 ft/day, indicating that (1) the sensors were within the circulation cell established by the GCW, and (2) the horizontal extent of groundwater circulation was greater than 15 feet. Furthermore, the groundwater flow direction data suggest that groundwater in the upper portion of the treatment zone generally flows radially away from the GCW and that groundwater in the bottom of the treatment zone generally flows radially towards the GCW. This flow direction data further support the establishment of a circulation cell and that all the flow sensors are within the horizontal extent of groundwater circulation cell.

- The data from the four modes of GCW operation suggest that the flow sensors are responsive to changes in groundwater flow conditions and can be used to help define and evaluate the three-dimensional flow pattern created by the GCW. The immediate response of the sensors to changes in GCW operation suggest that the groundwater circulation cell is established within hours instead of days. Additionally, the velocity data from the flow sensors suggest that the GCW circulation flow was generally constant during operation in the circulation mode.

Secondary Conclusions

S1 Evaluate the reproducibility of the groundwater velocity sensor data

- The reproducibility of the sensors during steady state conditions ranged from 0.1 to 23 percent with an average of 1.9 percent and a standard deviation of 3.8 percent.

S2 Evaluate the three-dimensional groundwater flow surrounding the GCW

- Groundwater flow patterns, as measured by the flow sensors, were documented for each of the four GCW operational modes and are depicted graphically to illustrate general flow patterns in the vicinity of the GCW during each mode of operation.

S3 Document the operating parameters of the GCW

- GCW pumping rate, duration of system operation, and GCW shutdowns were documented for each of the four modes of operation:

GCW Operational Mode	Pumping Rate	Duration of Operation	GCW Shutdowns
Circulation	4 gpm	July 10 – 28, 2000	1 shutdown for mechanical maintenance
Pump and Treat	4 gpm	August 2 – 29, 2000	7 shutdowns for mechanical repairs
Aquifer Hydraulic Testing	Various	September 13 – 19, 2000	None
Natural Conditions	No pumping	GCW not operated	GCW not operated

S4 Document the hydrogeologic characteristics at the demonstration site

- Natural groundwater flow velocities at the CCAS Facility 1381 site are very low, ranging from 0.03 to 0.21 ft/day (0.009 to 0.064 meter/day).

- The conductivity of the aquifer at the Facility 1381 site decreased with depth. Based on aquifer hydraulic test data, the hydraulic conductivity ranges from 43 to 53 ft/day (1.5×10^{-4} to 1.9×10^{-4} cm/s) for the shallow zone (upper 7 feet or 2.1 meters) and 5 to 10 ft/day (1.8×10^{-5} to 3.5×10^{-5} cm/s) for the deeper zone (7 to 25 feet deep or 7.6 meters). Storativity of the lower aquifer zone ranges from 0.006 to 0.007 and specific yield ranges from 0.06 to 0.09. The average anisotropic ratio (that is, the ratio of horizontal to vertical hydraulic conductivity) is 2.4, based on steady-state dipole flow test interpretation.

Additional findings and observations based on the EPA demonstration of the flow sensors include:

- According to the developer, the flow sensors measure flow in the a 3.3 cubic feet [1 cubic meter] area volume immediately surrounding the sensor,) and are subject to local heterogeneities. Complex site hydrogeological conditions may require a large number of flow sensors to adequately define the circulation cell and characterize flow patterns.

- To more fully evaluate the three-dimensional flow surrounding this GCW, additional sensors should have been installed at varying distances and depths from the GCW. Flow sensors should be installed at upgradient, downgradient, and cross-gradient locations at a minimum of three different distances from the GCW. The flow sensors also should be installed at three different depths corresponding to shallow and deep GCW screens as well as in the middle portion of the monitored zone between the two screens. The shallow sensors should be installed a minimum of 5 feet (1.5 meters) below the water table, which would minimize the impact of temperature variations caused by the vadose zone. Only seven sensors were installed for this project because preliminary modeling indicated that the circulation cell would be smaller than what was actually observed.

- HydroTechnics recommends installing the flow sensors with five feet (1.5 meters) of submergence because the shallow portion of the groundwater will heat up during the day, creating a thermal gradient that the sensor measures as water flow. For the EPA demonstration, the shallow sensors were installed with less than 5 feet of submergence because preliminary modeling indicated that there would not be significant flow deeper than 3 feet (1 meter) into the formation. Data from the shallow sensors were successfully corrected by subtracting the background temperature gradient.

- HydroTechnics recommends allowing at minimum of 7 days for the sensors to come to thermal equilibrium. During the EPA demonstration, short-term aquifer tests resulted in large but short-term changes in groundwater flow, that were successfully measured by the flow sensors.

- The cost of a single flow sensor was $2,500. The total cost for the seven sensors, sensor data analysis for a period of 1 year, and installation was $70,000 for this project. Costs at other sites may vary depending on installation depth and subsurface conditions.

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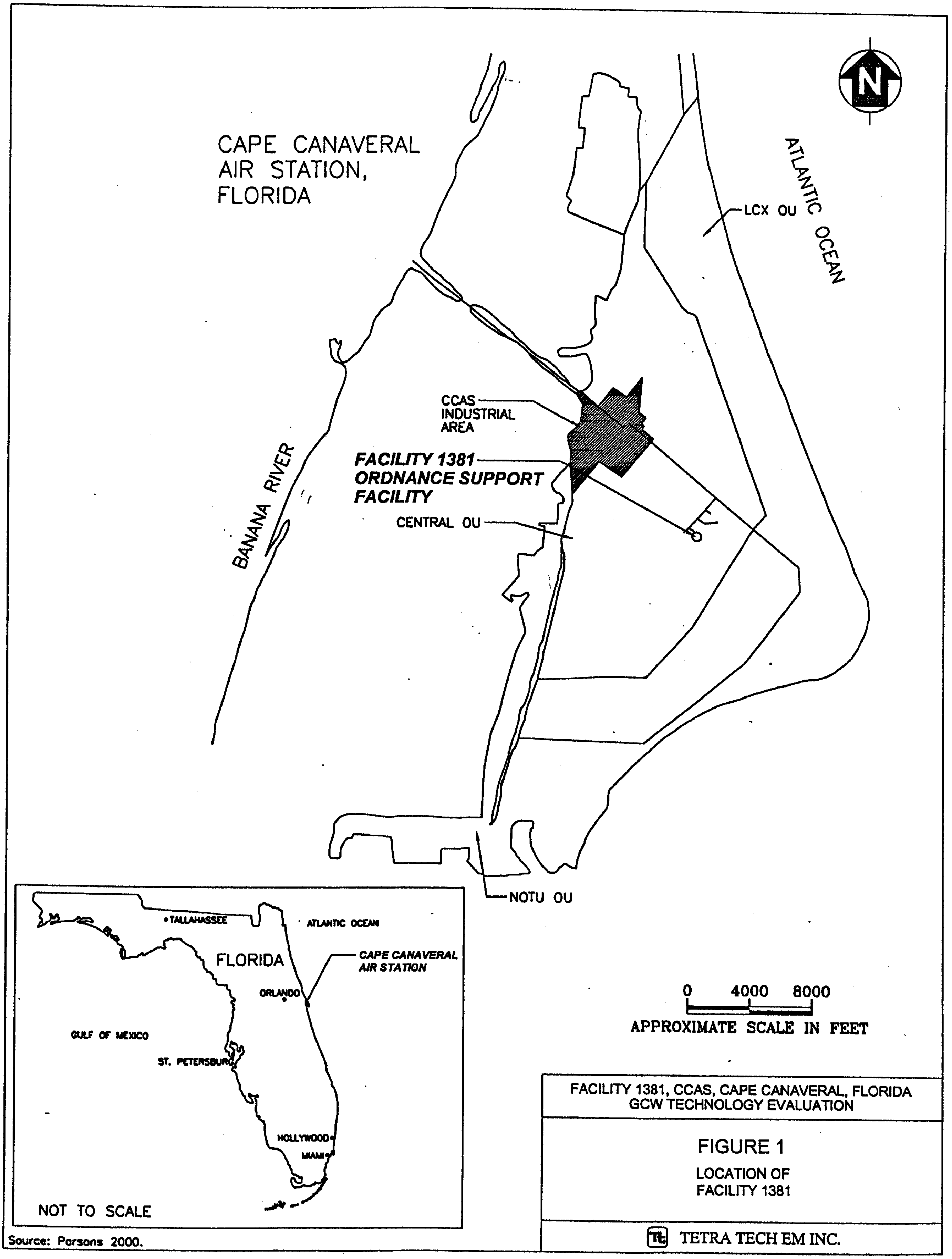
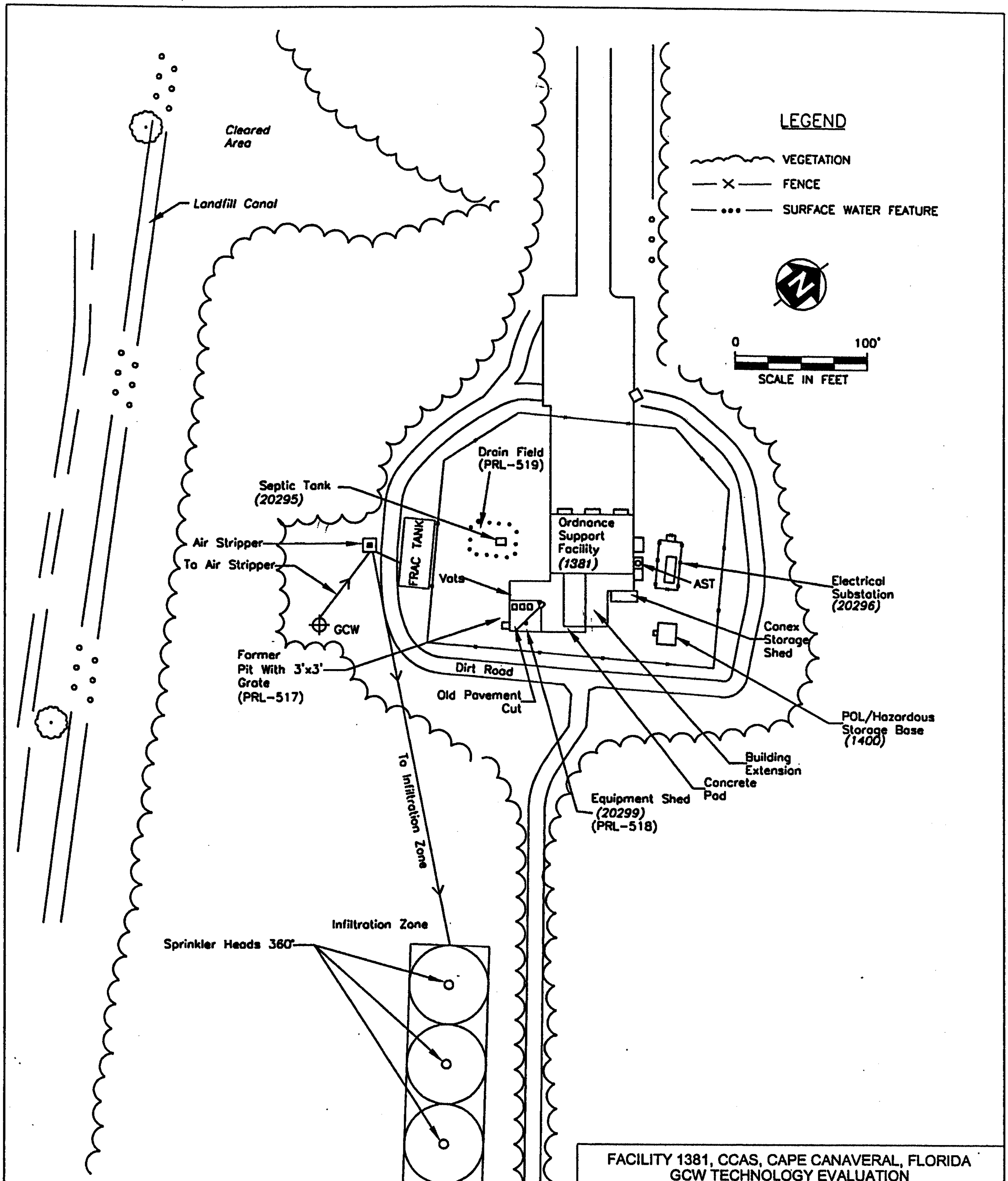
The following figures and tables are referred to in the main body of text for “Technology Evaluation Report: Hydrotechnics In Situ Flow Sensor.”



FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 1
LOCATION OF
FACILITY 1381

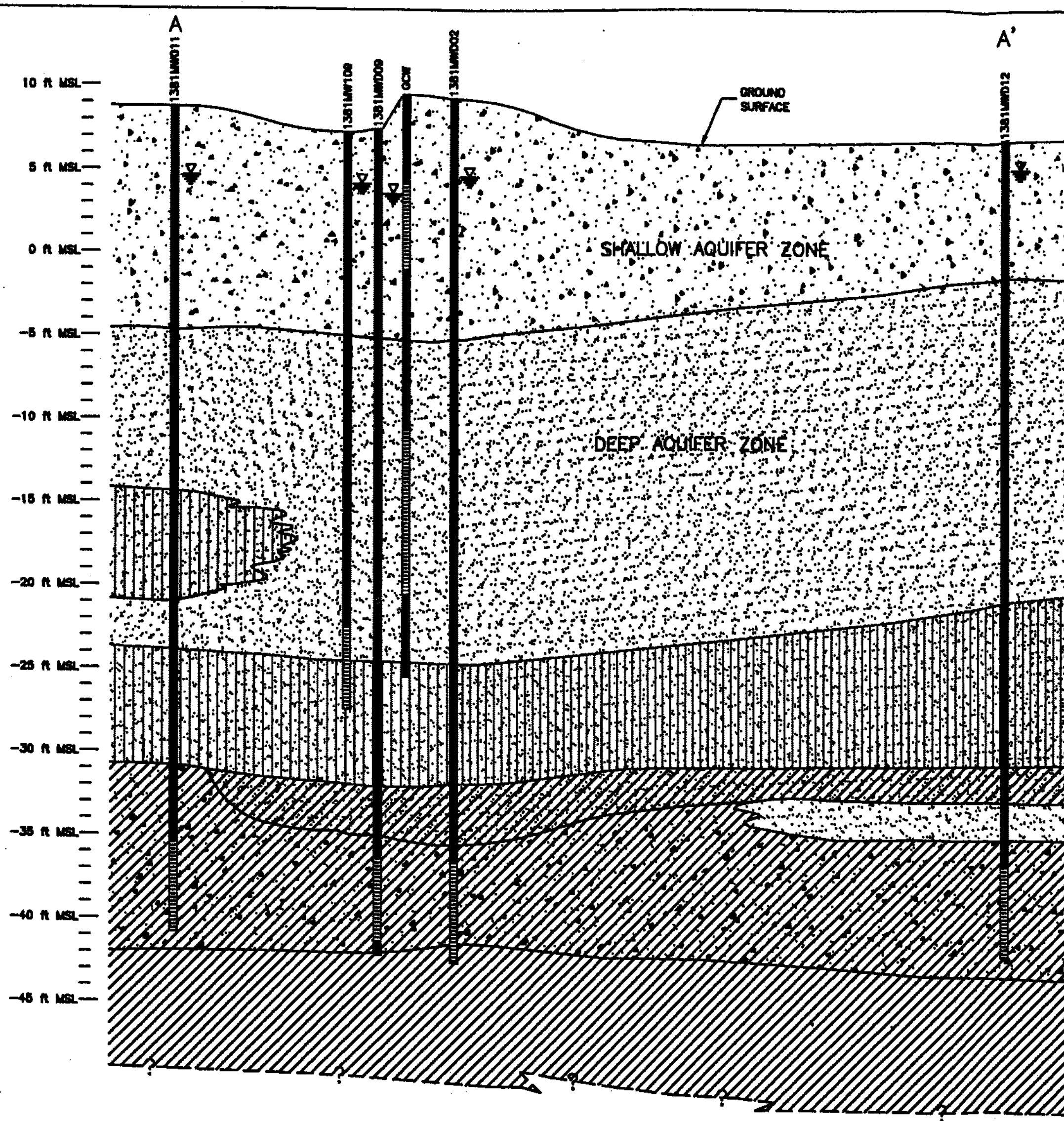
TETRA TECH EM INC.



FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 2
SITE MAP

TETRA TECH EM INC.



NOTES: 1) Location of GCW was projected onto cross section line.
2) Location of GCW is approximate.

140' 0 140' 280'
APPROXIMATE SCALE IN FEET

Source: Parsons 2000

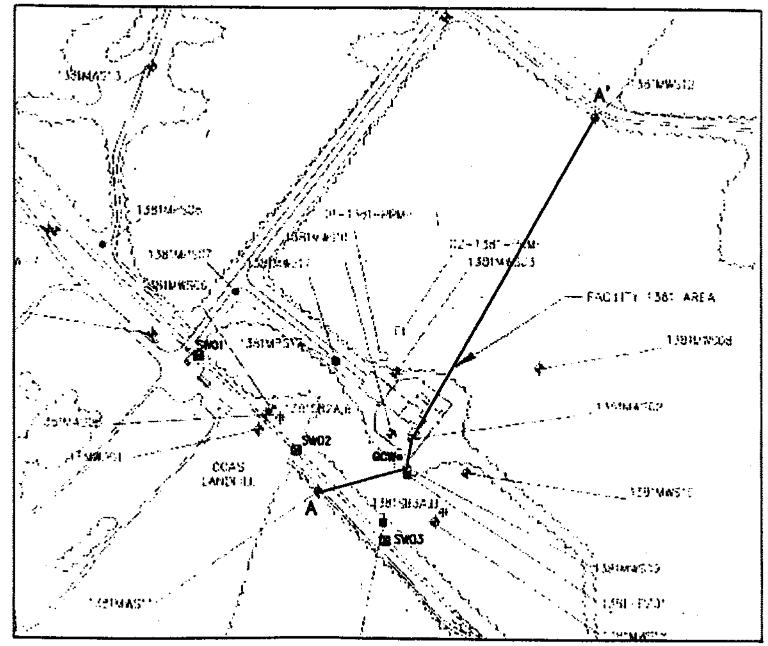
LEGEND

- WELL SCREEN
- WELL CASING
- GROUNDWATER LEVELS
- SHALLOW AQUIFER ZONE
- DEEP AQUIFER ZONE

LITHOLOGIES

- DOMINANTLY COARSE SHELL FRAGMENTS AND COARSE TO MEDIUM SAND, WITH LITTLE OR NO SILT AND, NO CLAY.
- DOMINANTLY MEDIUM TO VERY FINE SAND, WITH LITTLE OR NO SILT OR CLAY. MAY CONTAIN SIGNIFICANT SHELL FRAGMENTS.
- DOMINANTLY FINE TO VERY FINE SAND, WITH "SOME SILT" TO "AND SILT", LITTLE OR NO CLAY. MAY CONTAIN SHELL FRAGMENTS.
- DOMINANTLY FINE TO VERY FINE SAND, AND SILT, WITH "SOME CLAY" TO "AND CLAY".
- DOMINANTLY COARSE SHELL FRAGMENTS AND COARSE TO MEDIUM SAND, WITH "SOME CLAY" TO "AND CLAY", WITH OR WITHOUT MINOR AMOUNTS OF SILT.
- DOMINANTLY FIRM CLAY, MAY CONTAIN MINOR AMOUNTS OF SILT AND/OR SHELL FRAGMENTS.

10 ft MSL DEPTH IN FEET ABOVE MEAN SEA LEVEL



CROSS-SECTION LOCATION
APPROXIMATE SCALE: 1" = 400'

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 3
HYDROGEOLOGIC
CROSS-SECTION A-A'

TETRA TECH EM INC.

GEOLOGICAL UNITS
(ADAPTED FROM FAULKNER, 1973, FIG. 2)

Era	System		Series		Stratigraphic Unit	Thickness (feet)	Lithology	Aquifer (From Chapter 8)
CENOZOIC	QUATERNARY		Holocene		Unnamed alluvial, lake, and winddblown deposits	0–75	Alluvium freshwater marl, peats and muds in stream and lake bottoms. Also, some dunes and other windblown sand.	SURFICIAL AQUIFER
			Pleistocene		Pamlico Formation and marine and estuarine terrace deposits	0–75	Mostly marine quartz sand, unconsolidated and generally well graded. Also, some fluviatile and lacustrine sand, clay, marl, and peat deposits.	
	TERTIARY		Pliocene		Jackson Bluff Formation	0–75±	Marine sands, argillaceous, carbonaceous, and sandy shell marl. Some phosphatic limestone.	
					Alachua Formation	0–100±	Nonmarine interbedded deposits of clay, sand, and sandy clay; much of unit is phosphatic, base characterized by rubble of phosphate rock and silicified limestone residuum in a gray and green phosphatic clay matrix.	
			Miocene		Fort Preston[1] Formation	0–100±	Nonmarine fluviatile sand, white to gray, variegated orange, purple and red in upper part, fine- to coarse-grained to pebbly, clayey, crossbedded.	
					Hawthorn Formation	0–300±	Marine interbedded sand, cream, white, and gray, phosphatic, often clayey; clay, green to gray and white, phosphatic, often sandy; dolomite, cream to white and gray, phosphatic, sandy, clayey, and some limestone, hard, dense, in part sandy and phosphatic. Tends to be sandy in upper part and dolomitic and limy in lower part.	
		LOWER	Oligocene		Suwannee Limestone	0–150	Marine limestone, very pale orange, finely crystaline, small amounts of silt and clay.	FLORIDAN AQUIFER SYSTEM
			Eocene	Upper	[2]Ocala Limestone – Upper[3] Member	0–325	Marine limestone, cream to white, soft, granular, highly porous, coquinal; often consists entirely of tests of foraminifers; cherty in places.	
					Ocala Limestone – Lower[4] Member		Marine limestone, cream to tan and brown, granular, soft to firm, porous, highly fossiliferous, lower part at places is dolomite, gray and brown, crystaline, saccharoidal, porous.	
				Middle	Avon Park Formation	500–1600	Marine limestone, light brown to brown, finely fragmental, poor to good porosity, highly fossiliferous (mostly foraminifers); and dolomite, brown to dark brown, slightly porous to good porosity, crystaline, saccharoidal; both limestone and dolomite are carbonaceous or peaty; gypsum is present in small amounts. Marine limestone, light brown to brown, fragmental, highly fossiliferous, slightly carbonaceous or peaty and cherty; and dolomite, brown to dark brown with very minor amounts of gypsum and anhydrite. Unit is slightly porous to porous.	
				Lower	Oldsmar Formation	300–1350	Marine limestone, light brown to chalky, white, porous, fossiliferous, with interbedded brown, porous, crystaline dolomite; minor amounts of anhydrite and gypsum.	
			Paleocene		Cedar Keys Formation	500–2200	Marine dolomite, light gray, hard, slightly porous to porous, crystaline, in part fossiliferous, with considerable anhydrite and gypsum, some limestone.	
MESOZOIC	Cretaceous				Upper and Lower Cretaceous	1500–?	Mostly marine Upper Cretaceous carbonate and evaporite rocks, sands and shales, thin Lower Cretaceous clastic section in some of area.	
PALEOZOIC and PRECAMBRIAN					DEVONIAN to PRECAMBRIAN (?)	Basement Rocks	Marine Devonian, Silurian, and Ordovician quartzose sandstone and dark shale; lower Paleozoic (?) or Precambrian (?) rhyolite, tuff and agglomerate.	

[1] Usage of Bureau of Geology, Florida Department of Natural Resources.
[2] Ocala Group of Bureau of Geology, Florida Department of Natural Resources.
[3] Crystal River Formation of Ocala Group.
[4] Inglis Formation and Williston Formation (older to younger) of Ocala Group.

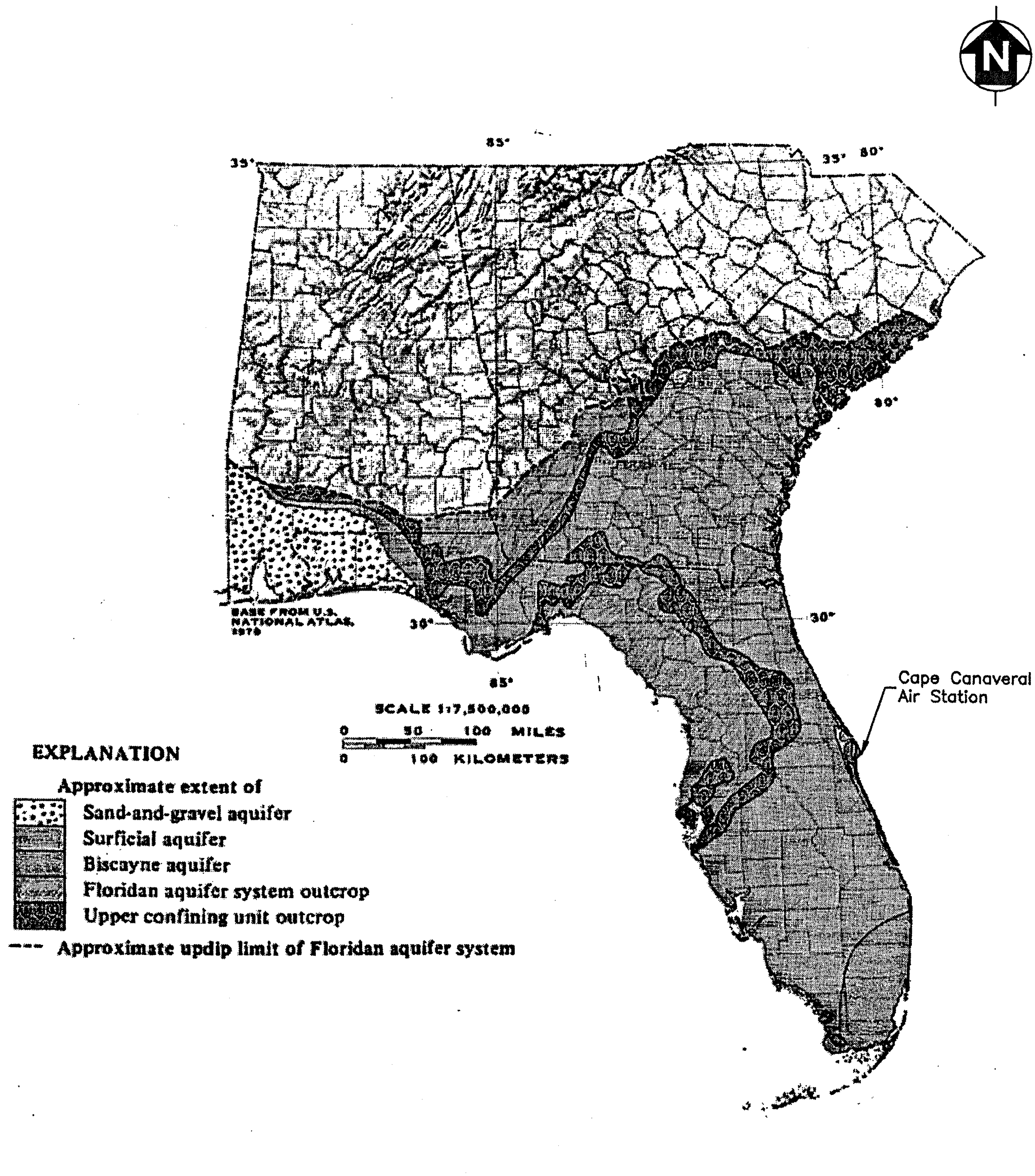
PRINCIPAL HYDROGEOLOGIC UNITS
(CONCEPTUAL MODEL)

SURFICIAL AQUIFER
UPPER CONFINING UNIT
UPPER FLORIDAN AQUIFER
MIDDLE SEMICONFINING UNIT
LOWER FLORIDAN AQUIFER
LOWER CONFINING UNIT (EXTREMELY LOW PERMEABILITY)
BASEMENT ROCKS

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 4
HYDROSTATIGRAPHIC UNITS
OF EAST CENTRAL FLORIDA

TETRA TECH EM INC.

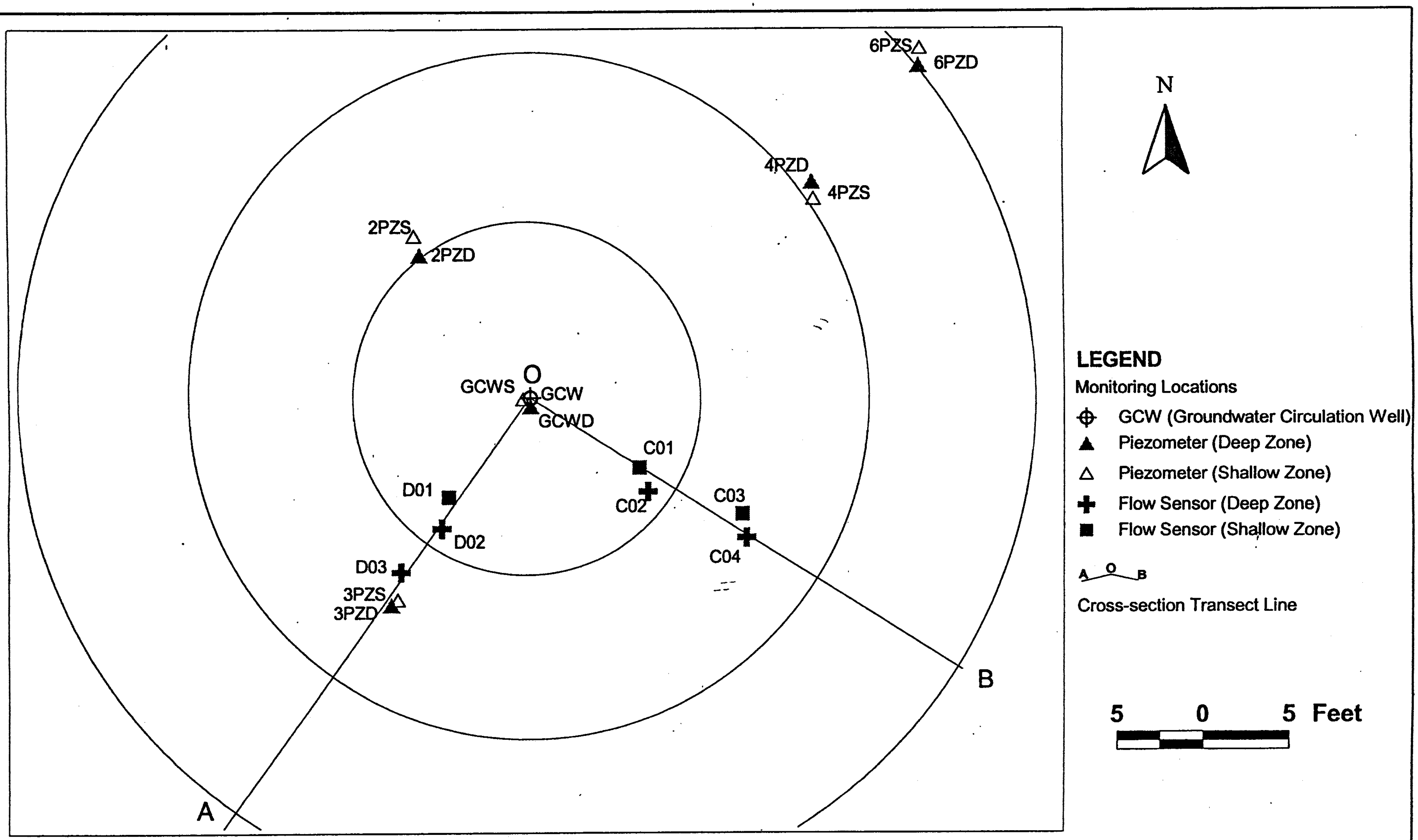


Source: Miller 1986

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 5
APPROXIMATE EXTENT OF THE SURFICIAL AQUIFER

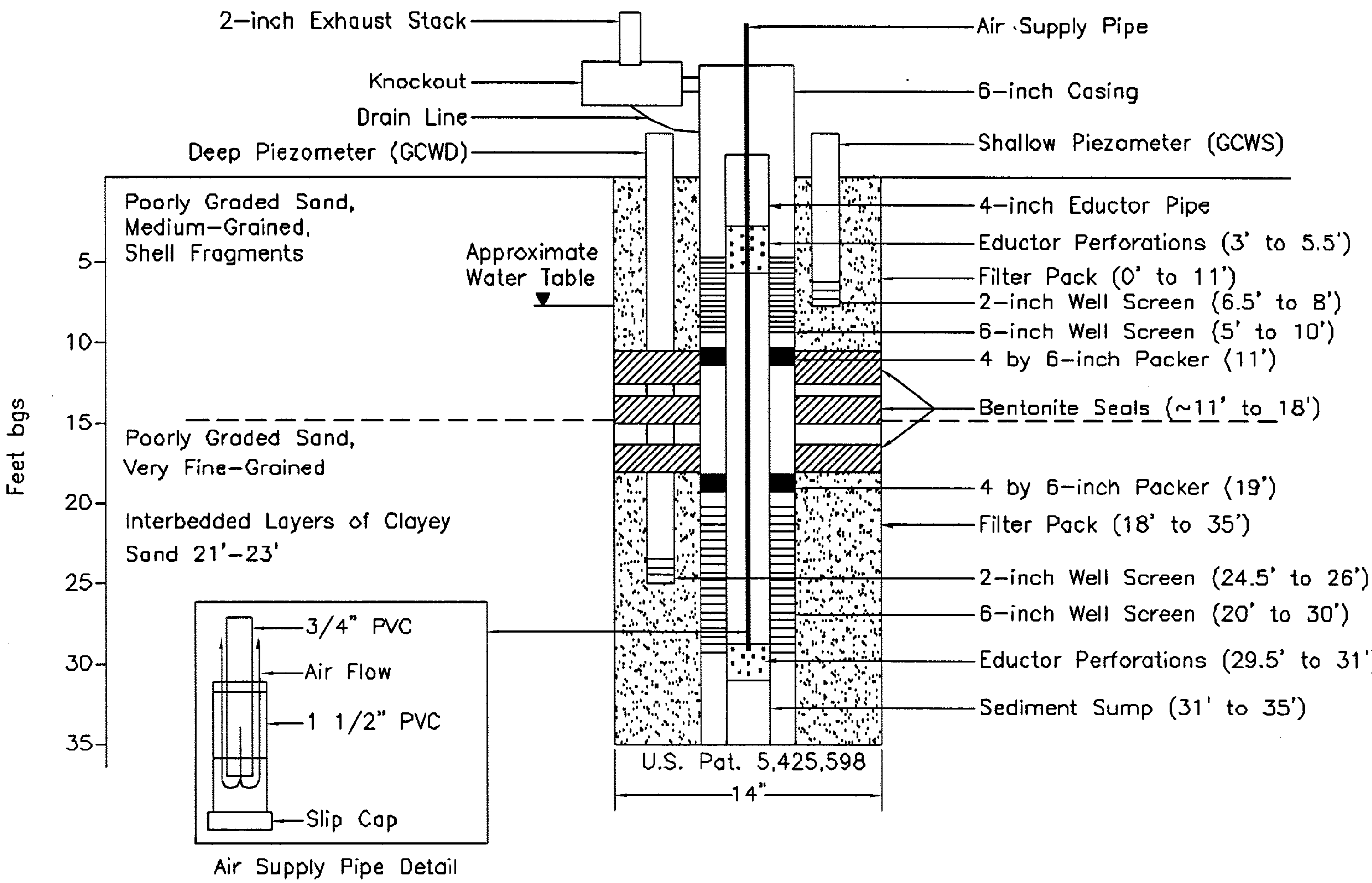
TETRA TECH EM INC.



FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 6
Locations of Groundwater Circulation Well, Piezometer and Groundwater Flow Sensors

Tetra Tech EM Inc.



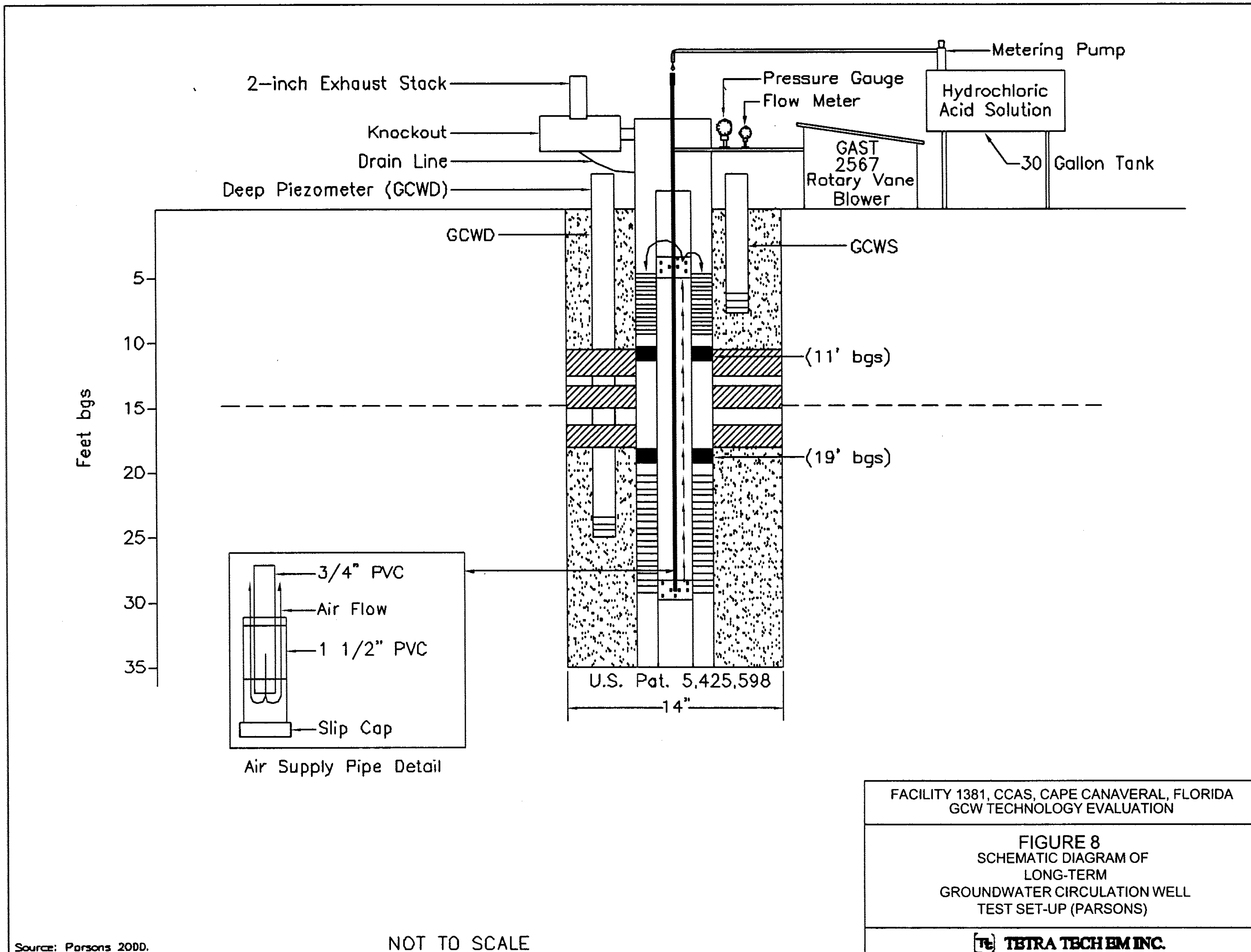
Source: Parsons 2000.

NOT TO SCALE

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 7
SCHEMATIC DIAGRAM OF GROUNDWATER CIRCULATION WELL AND PIEZOMETERS

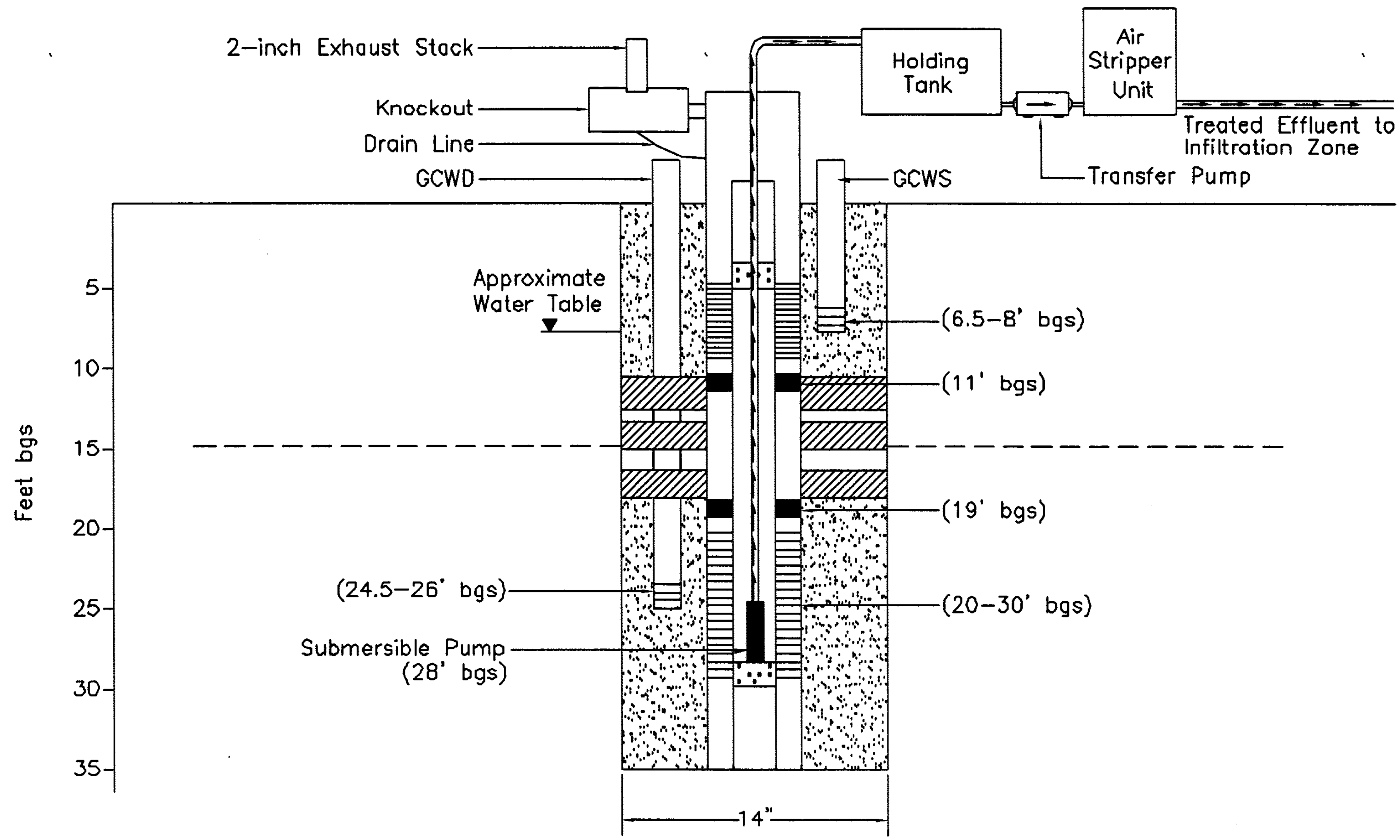
TETRA TECH EM INC.



FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 8
SCHEMATIC DIAGRAM OF
LONG-TERM
GROUNDWATER CIRCULATION WELL
TEST SET-UP (PARSONS)

TETRA TECH EM INC.



Source: Parsons 2000.

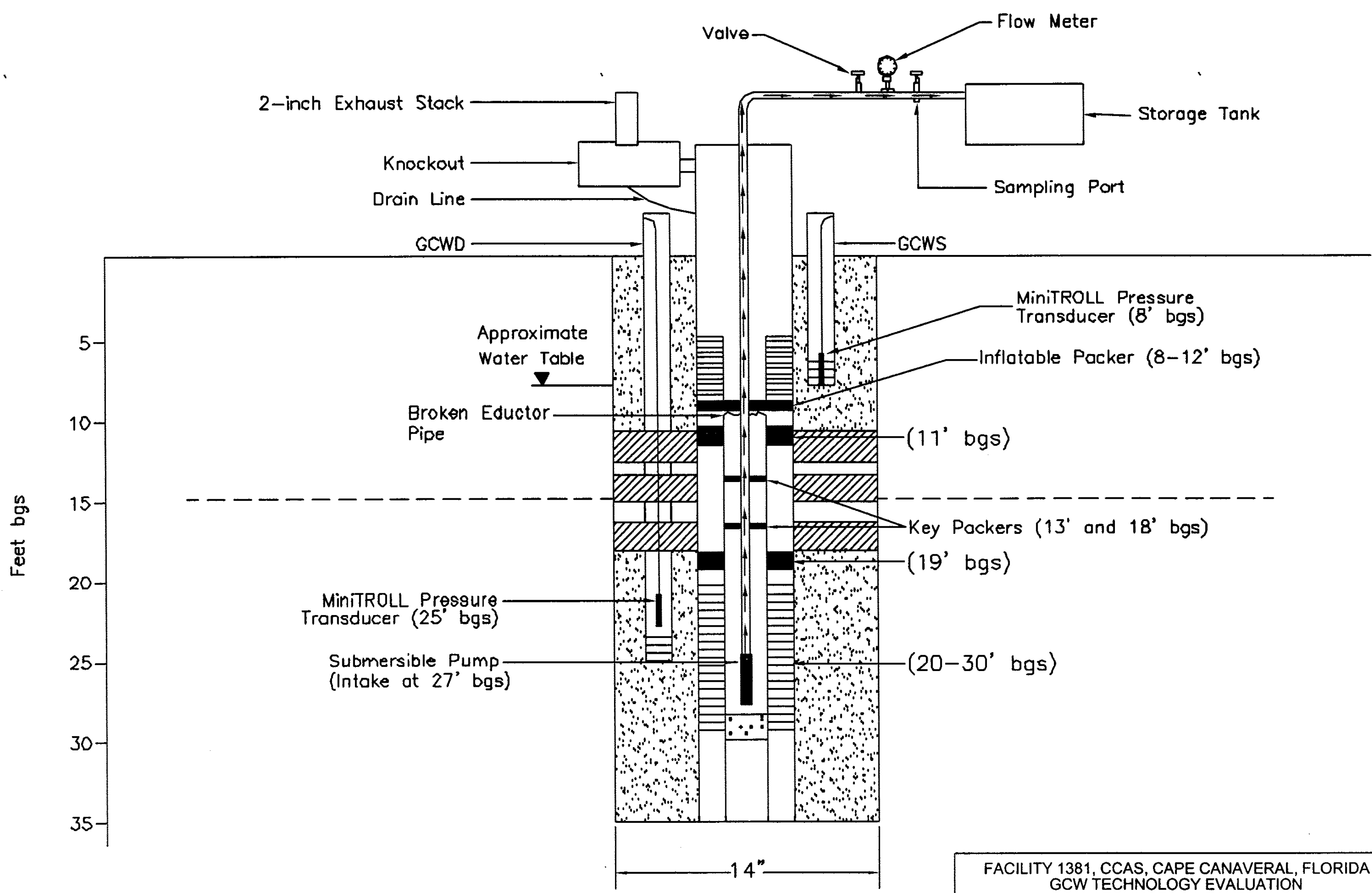
NOT TO SCALE

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 9

SCHEMATIC DIAGRAM OF FINAL PUMP-AND-TREAT TEST SET-UP

TETRA TECH EM INC.



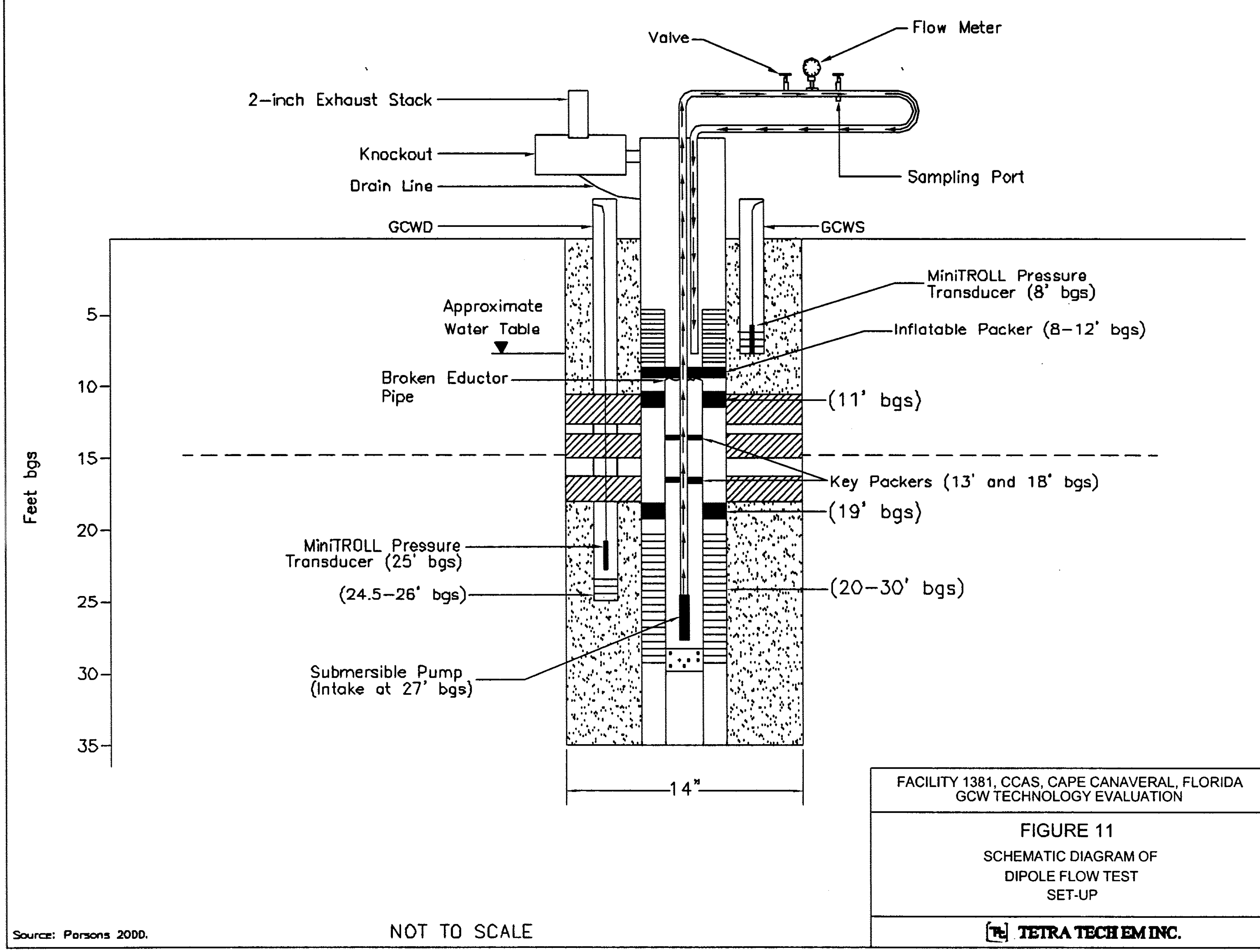
Source: Parsons 2000.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 10

SCHEMATIC DIAGRAM OF CONSTANT RATE PUMPING TEST SET-UP

TETRA TECH EM INC.

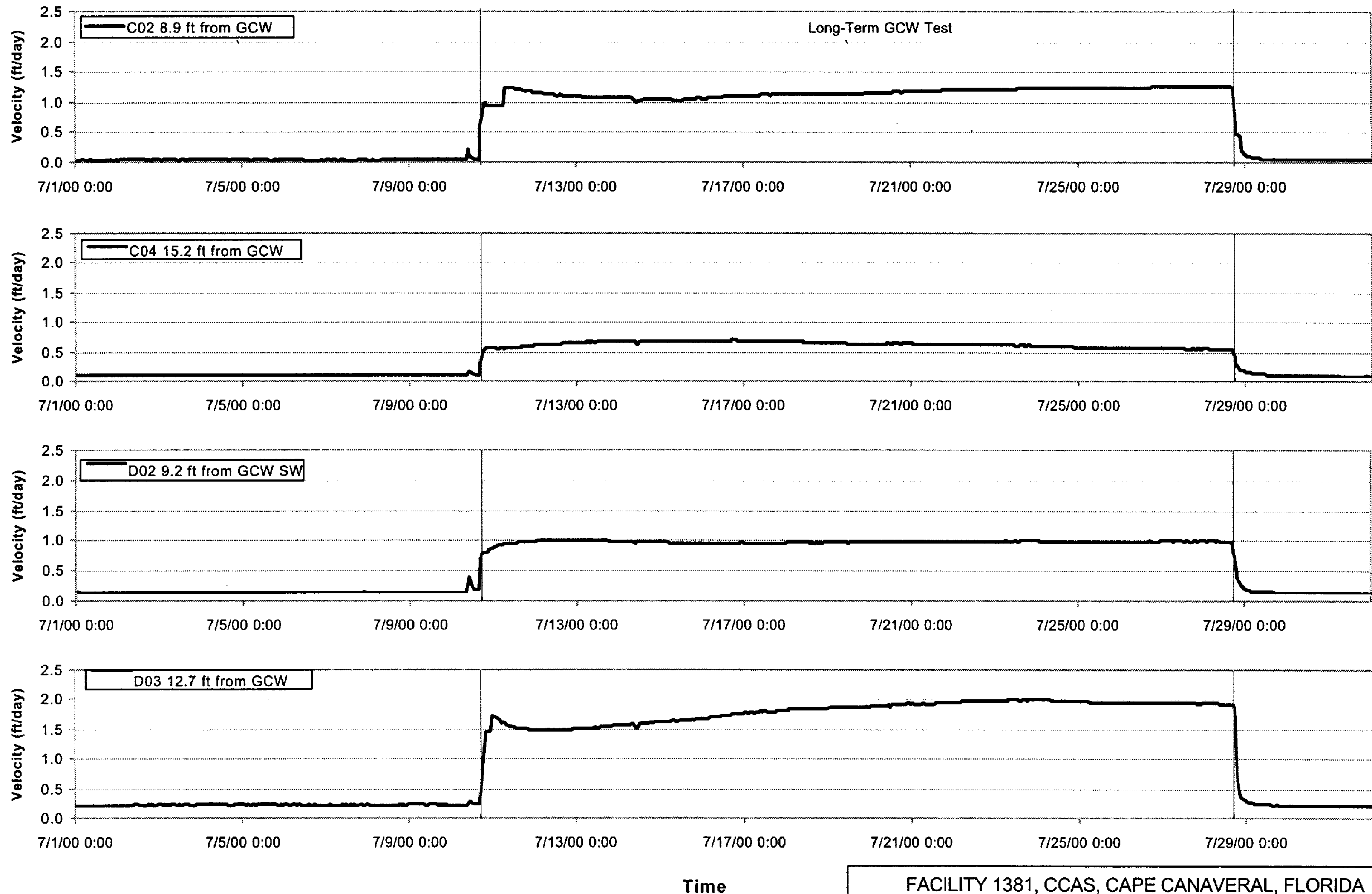


FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 11

SCHEMATIC DIAGRAM OF DIPOLE FLOW TEST SET-UP

TETRA TECH EM INC.

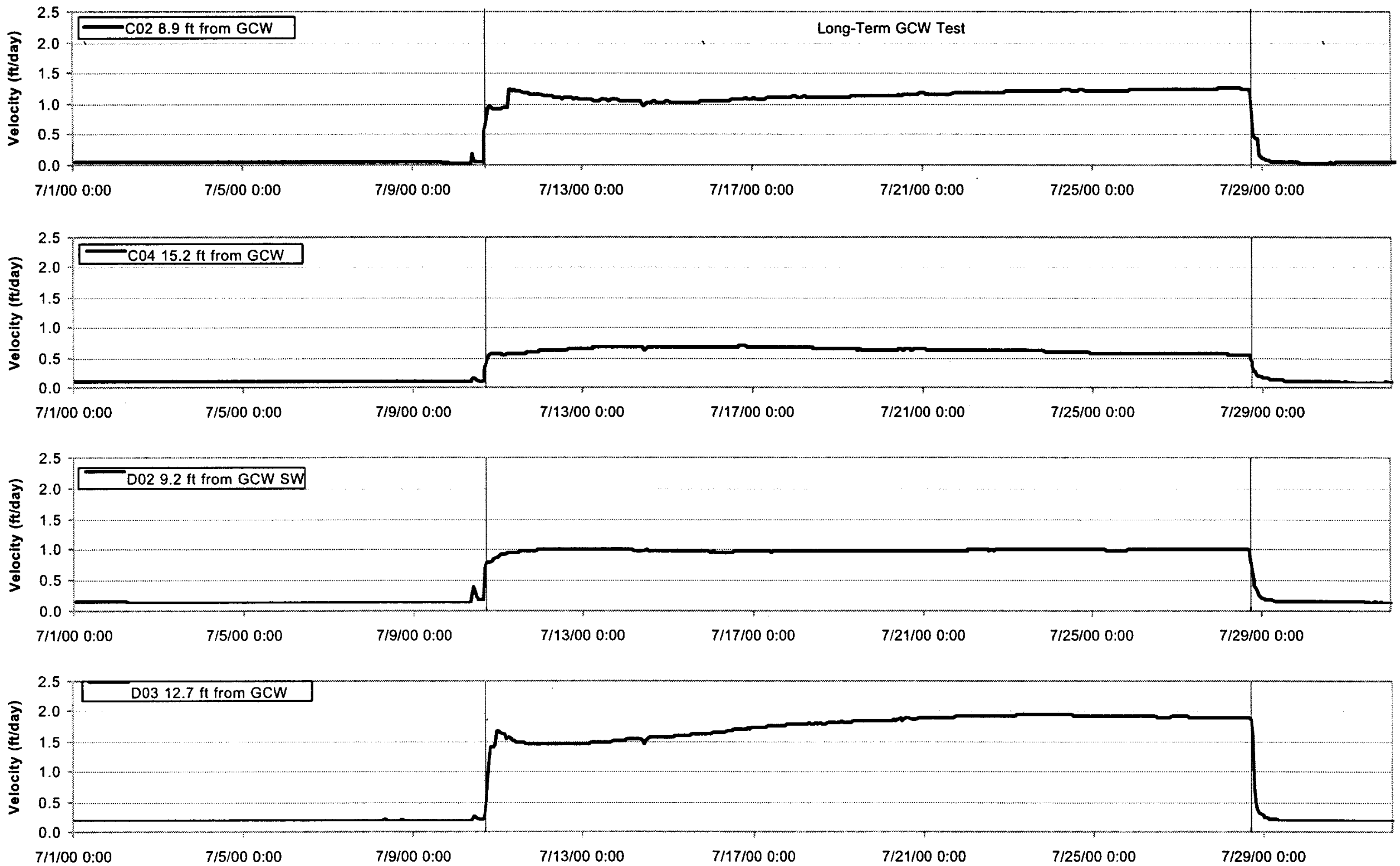


NOTES:
1) Data shown is from a long term GCW circulation test conducted by Parsons in July 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 12
Horizontal Groundwater Darcy Velocity Versus Time in Deep Aquifer Zone Measured by Flow Sensors 7/1/00 - 7/31/00 (Actual Data)

Tetra Tech EM Inc.

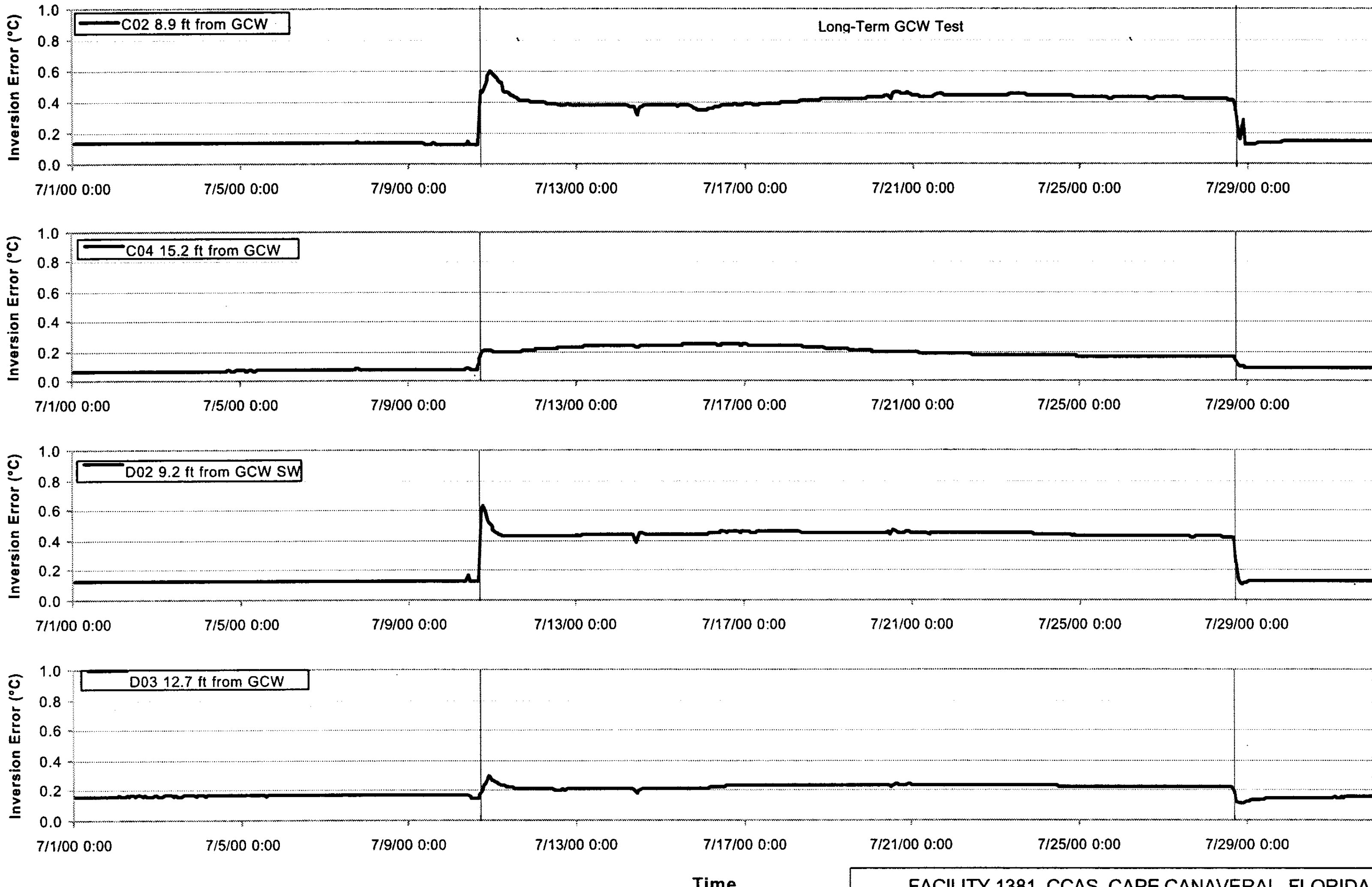


NOTES:
1) Data shown is from a long term GCW circulation test conducted by Parsons in July 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 13
Horizontal Groundwater Darcy Velocity Versus Time in Deep Aquifer Zone Measured by Flow Sensors 7/1/00 - 7/31/00 (Data with Background Removed)

Tetra Tech EM Inc.

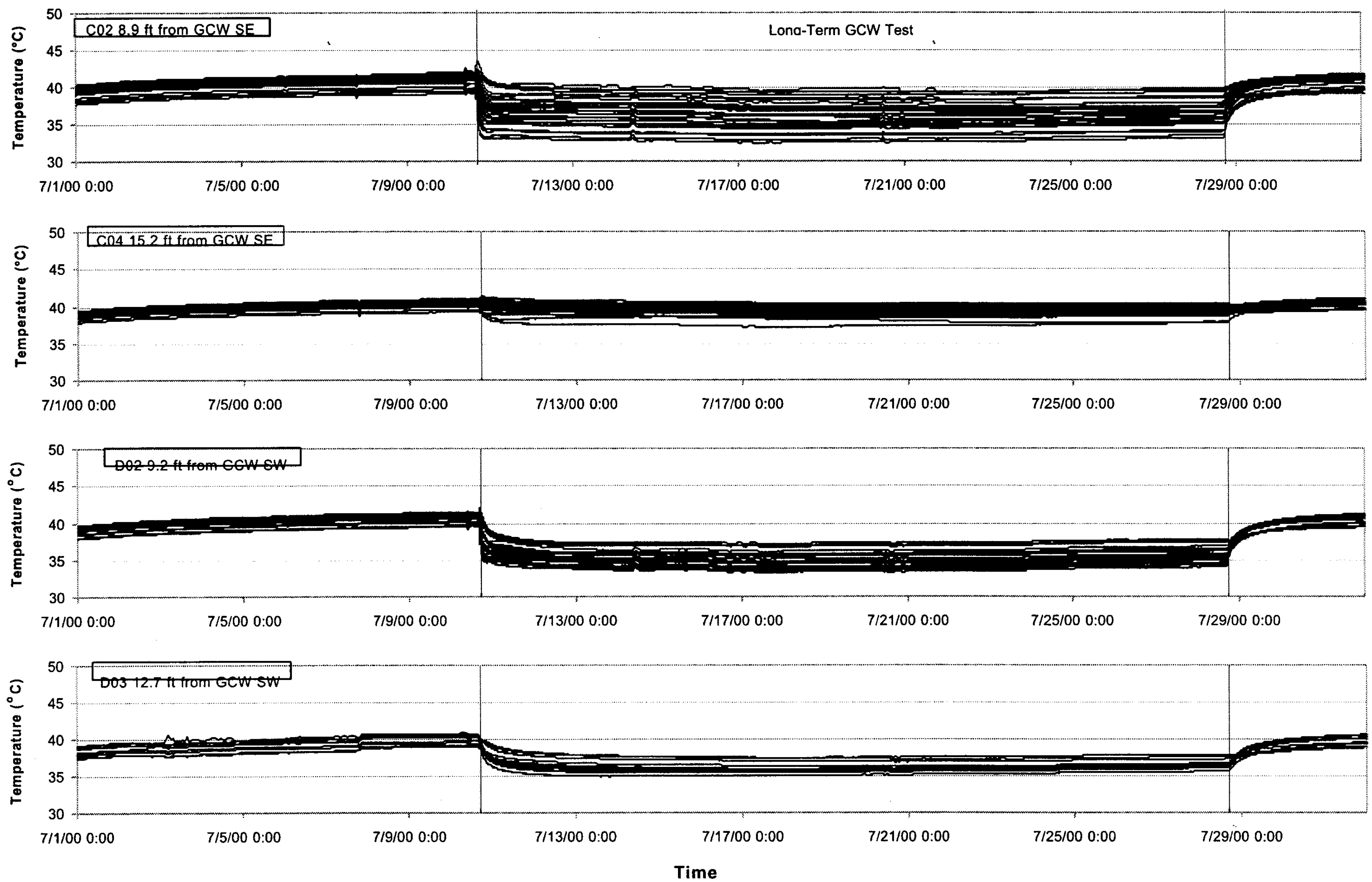


NOTES:
1) Data shown is from a long term GCW circulation test conducted by Parsons in July 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 14
Flow Sensor Inversion Errors Versus Time in Deep Aquifer Zone
7/1/00 - 7/31/00

Tetra Tech EM Inc.

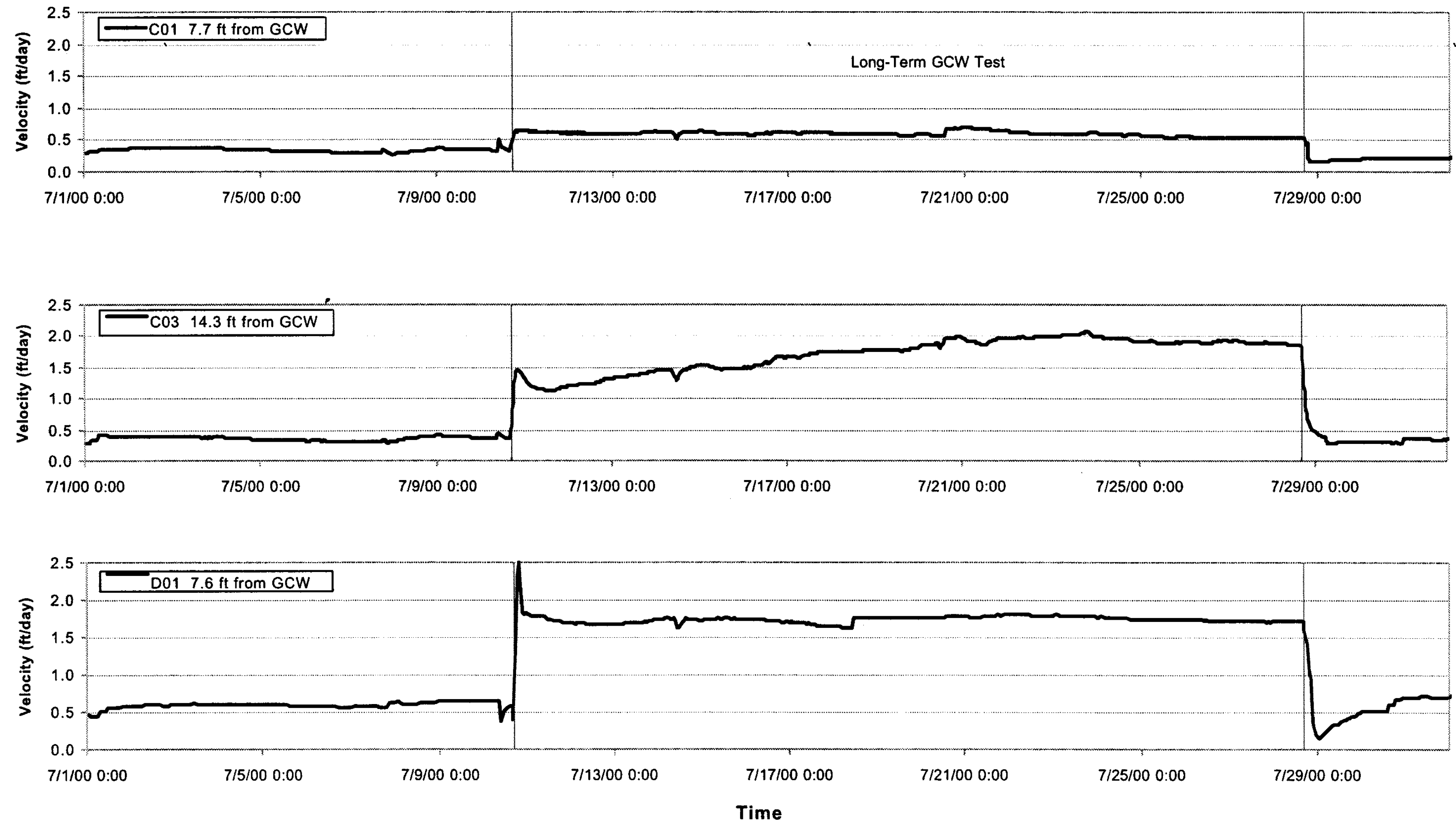


NOTES:
1) Data shown is from a long term GCW circulation test conducted by Parsons in July 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 15
Thermistor Temperature Versus Time in Deep Aquifer Zone Flow Sensors
7/1/00 - 7/31/00

Tetra Tech EM Inc.

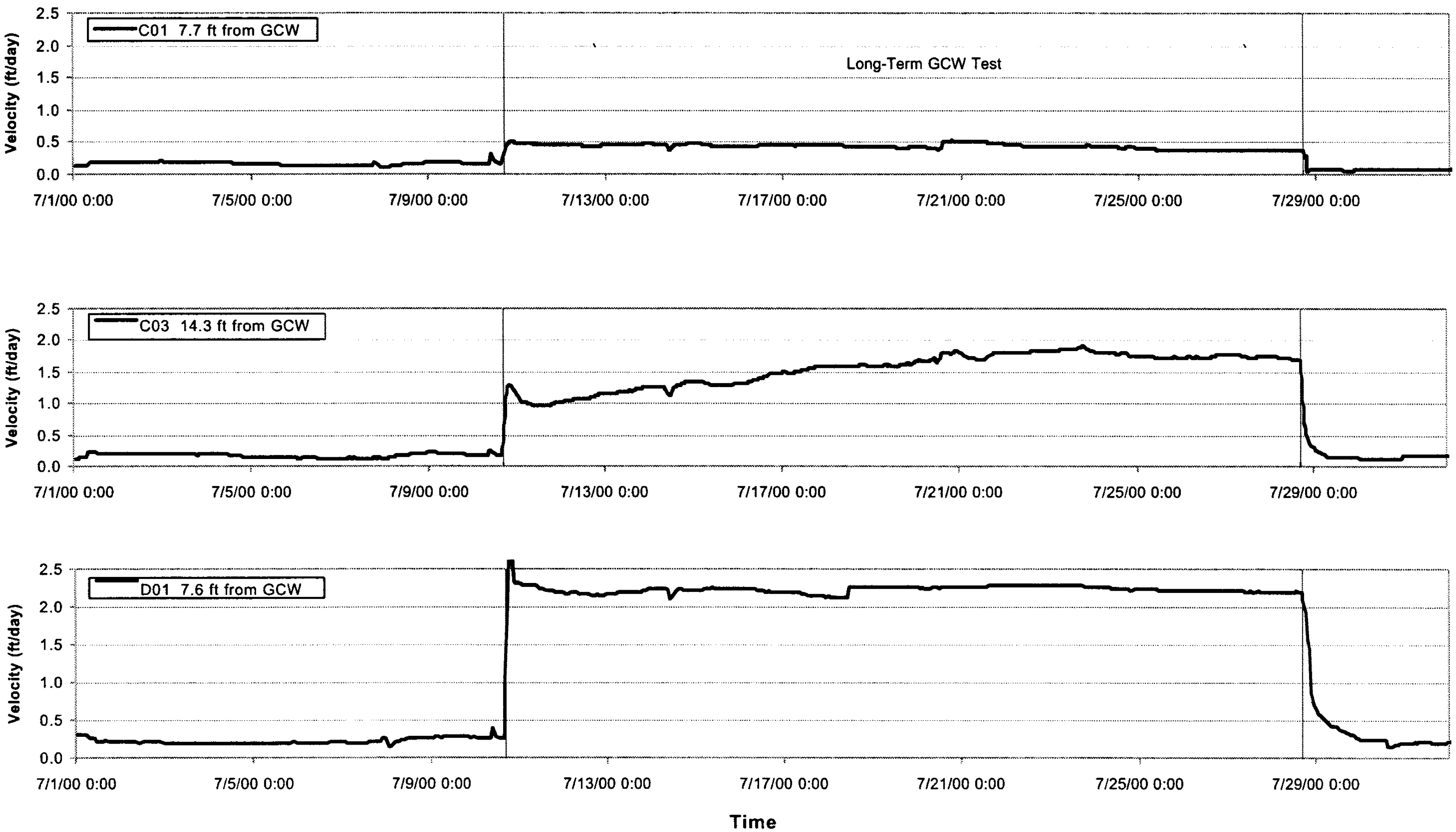


NOTES:
1) Data shown is from a long term GCW circulation test conducted by Parsons in July 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 16
Horizontal Groundwater Darcy Velocity Versus Time in Shallow Aquifer Zone Measured by Flow Sensors 7/1/00 - 7/31/00 (Actual Data)

Tetra Tech EM Inc.

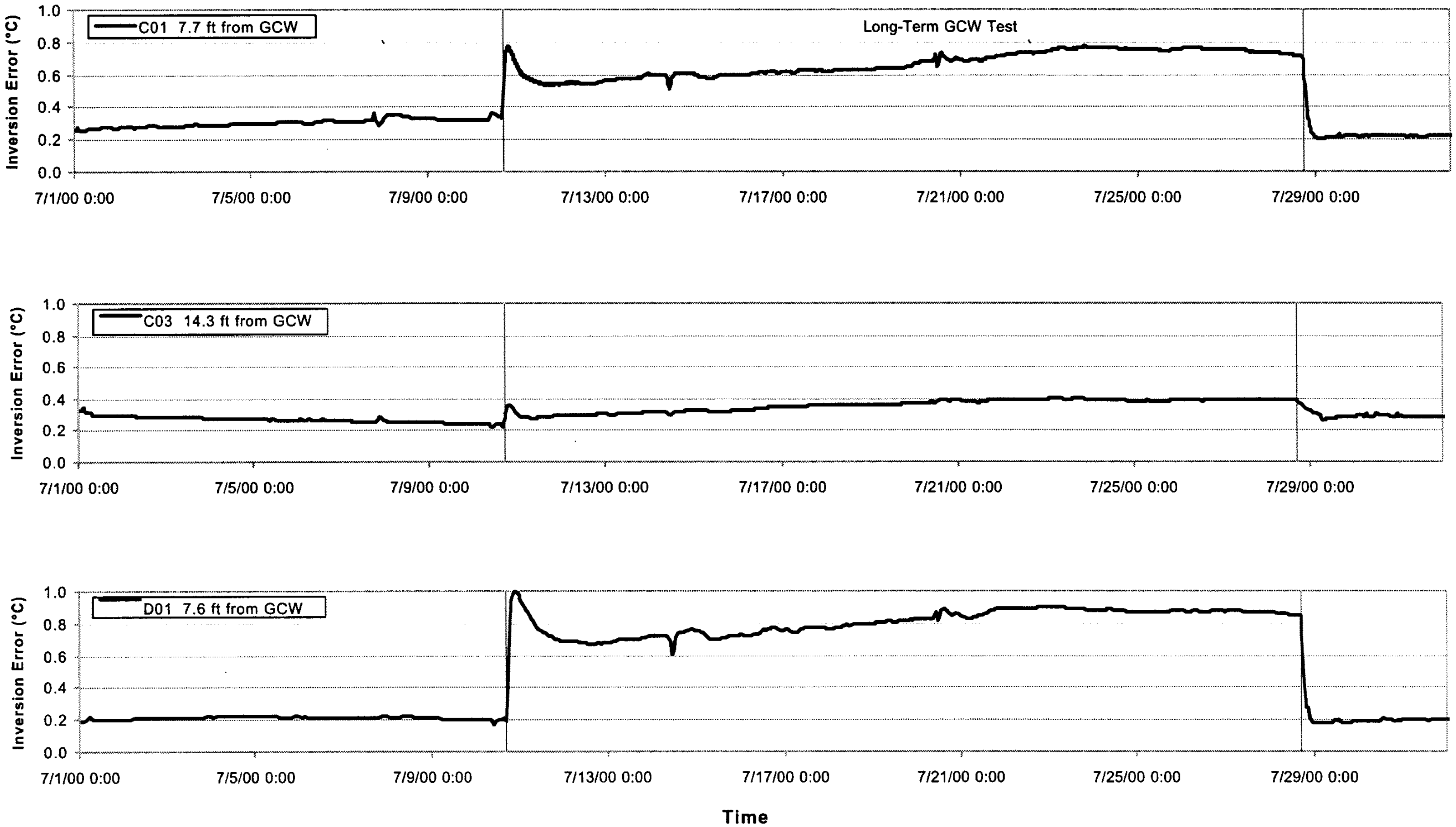


NOTES:
1) Data shown is from a long term GCW circulation test conducted by Parsons in July 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 17
Horizontal Groundwater Darcy Velocity Versus Time in Shallow Aquifer Zone Measured by Flow Sensors 7/1/00 - 7/31/00 (Data with Background Removed)

Tetra Tech EM Inc.

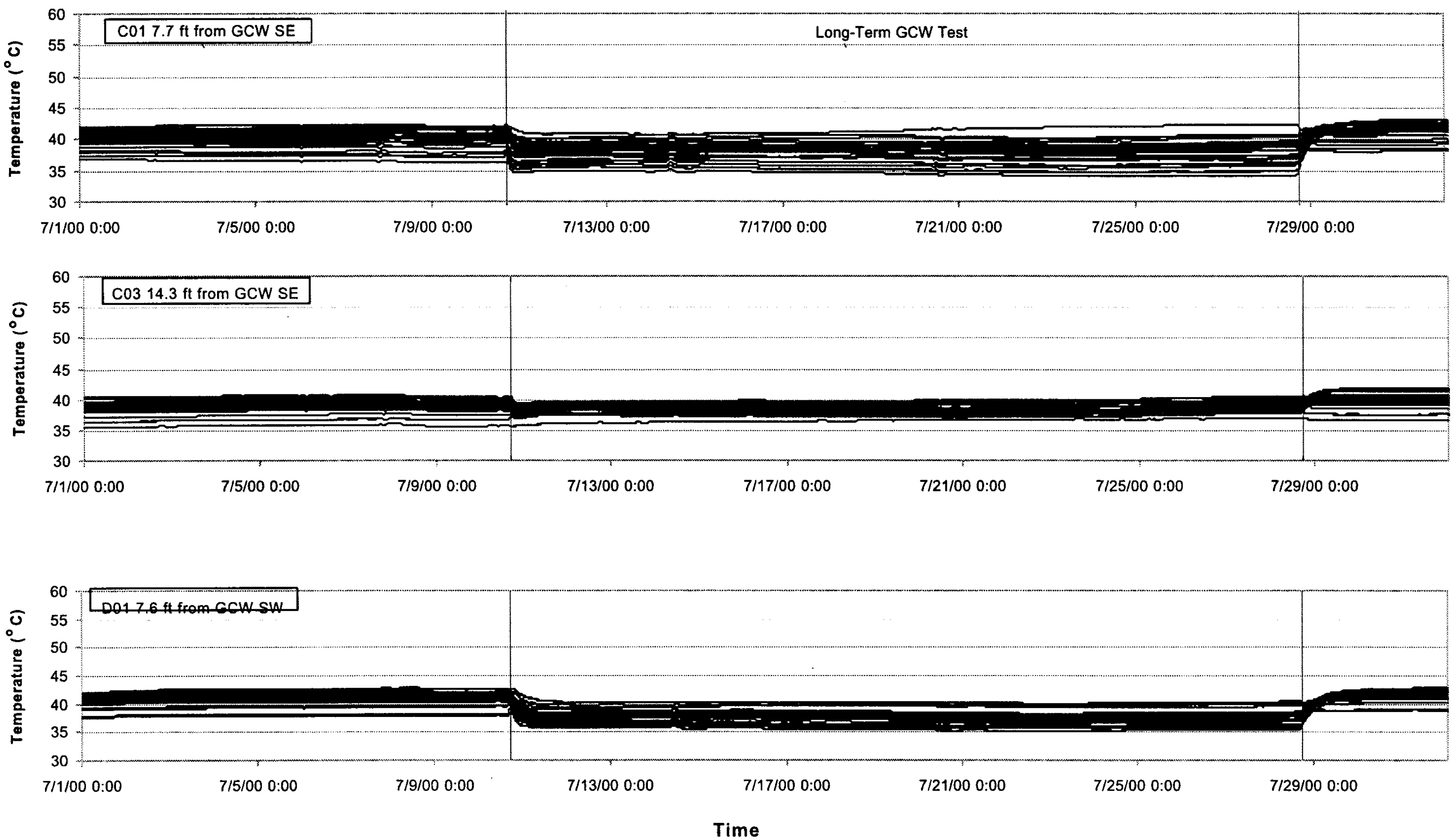


NOTES:
1) Data shown is from a long term GCW circulation test conducted by Parsons in July 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

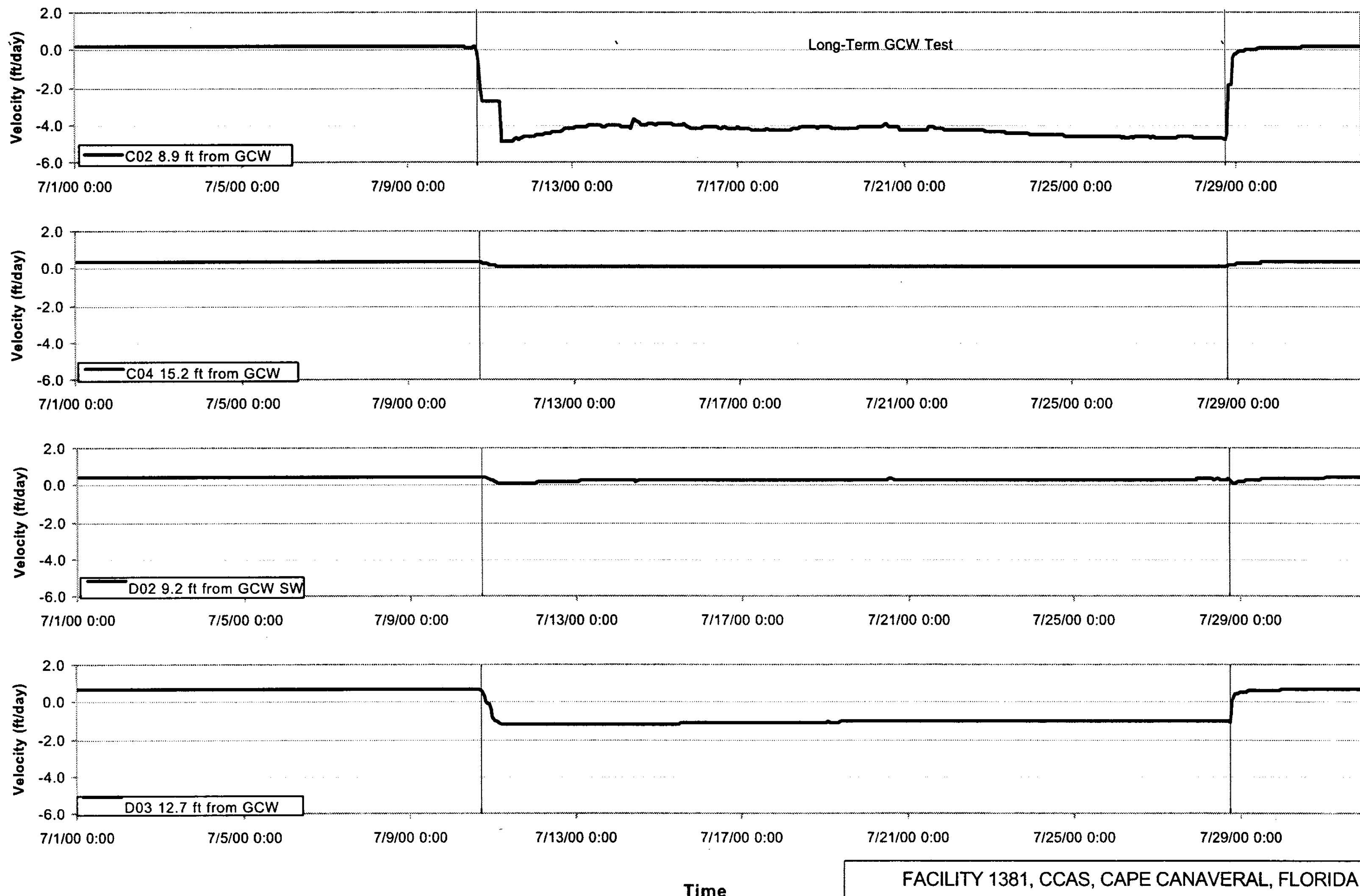
FIGURE 18
Flow Sensor Inversion Errors Versus Time in Shallow Aquifer Zone
7/1/00 - 7/31/00

Tetra Tech EM Inc.



NOTES:
1) Data shown is from a long term GCW circulation test conducted by Parsons in July 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA GCW TECHNOLOGY EVALUATION
FIGURE 19 **Thermistor Temperature Versus Time in Shallow Aquifer Zone Flow Sensors** **7/1/00 - 7/31/00**
Tetra Tech EM Inc.

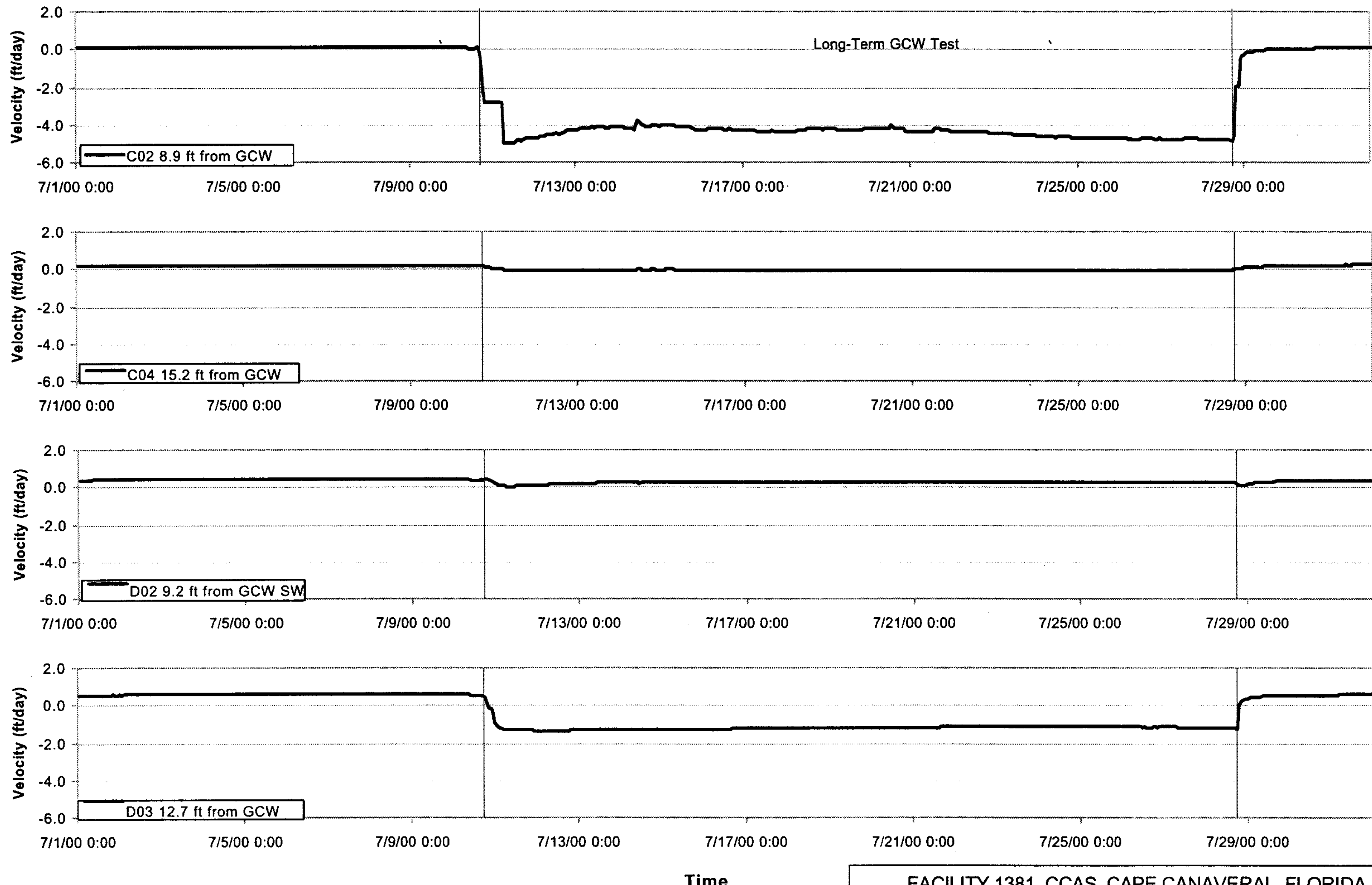


NOTES:
1) Data shown is from a long term GCW circulation test conducted by Parsons in July 2000.
2) Positive vertical velocity is indicative of upward hydraulic gradient.
3) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 20
Vertical Groundwater Darcy Velocity Versus Time in Deep Aquifer Zone Measured by Flow Sensors 7/1/00 - 7/31/00 (Actual Data)

Tetra Tech EM Inc.

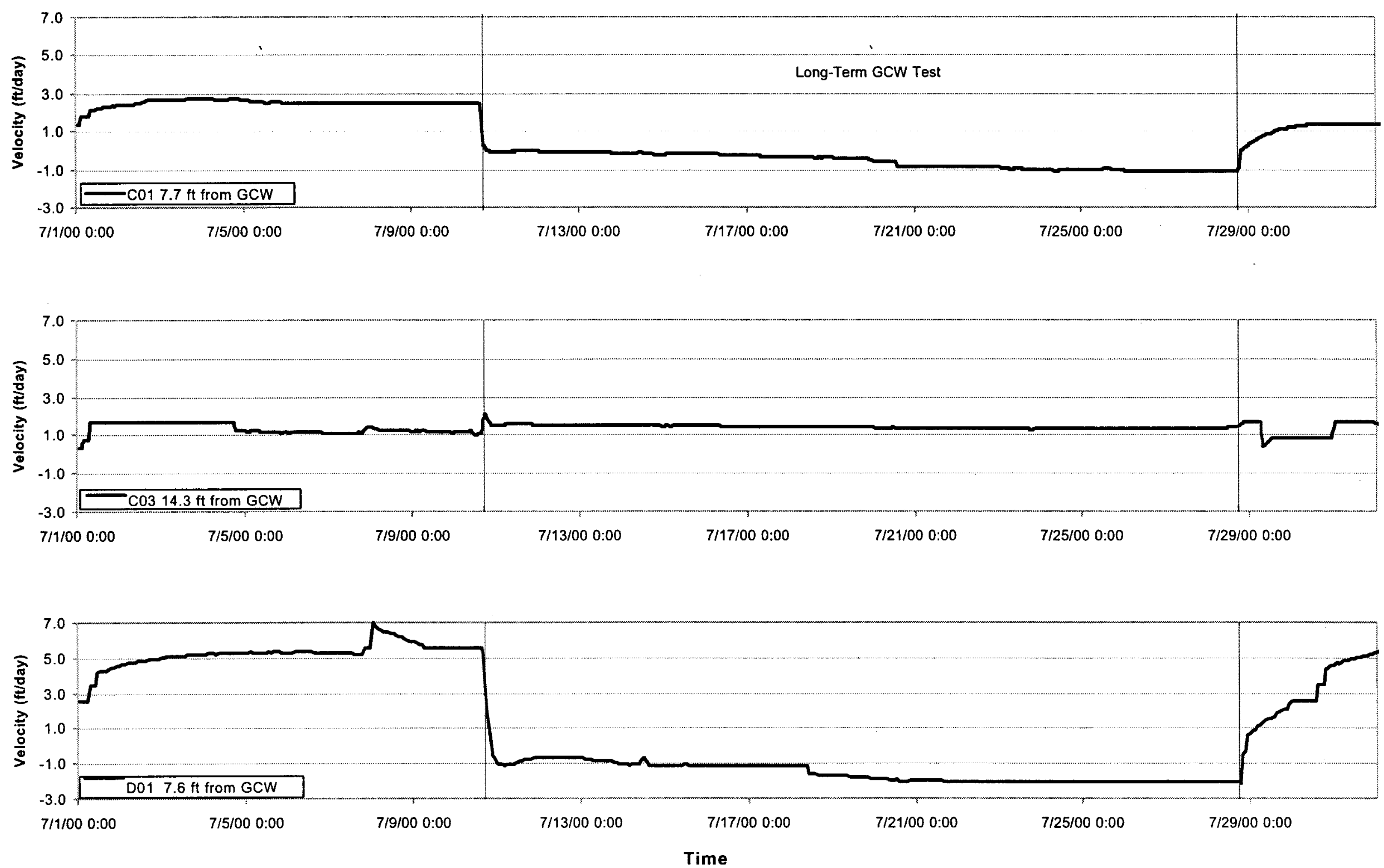


NOTES:
1) Data shown is from a long term GCW circulation test conducted by Parsons in July 2000.
2) Positive vertical velocity is indicative of upward hydraulic gradient.
3) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 21
Vertical Groundwater Darcy Velocity Versus Time in Deep Aquifer Zone Measured by Flow Sensors 7/1/00 - 7/31/00 (Data with Background Removed)

Tetra Tech EM Inc.

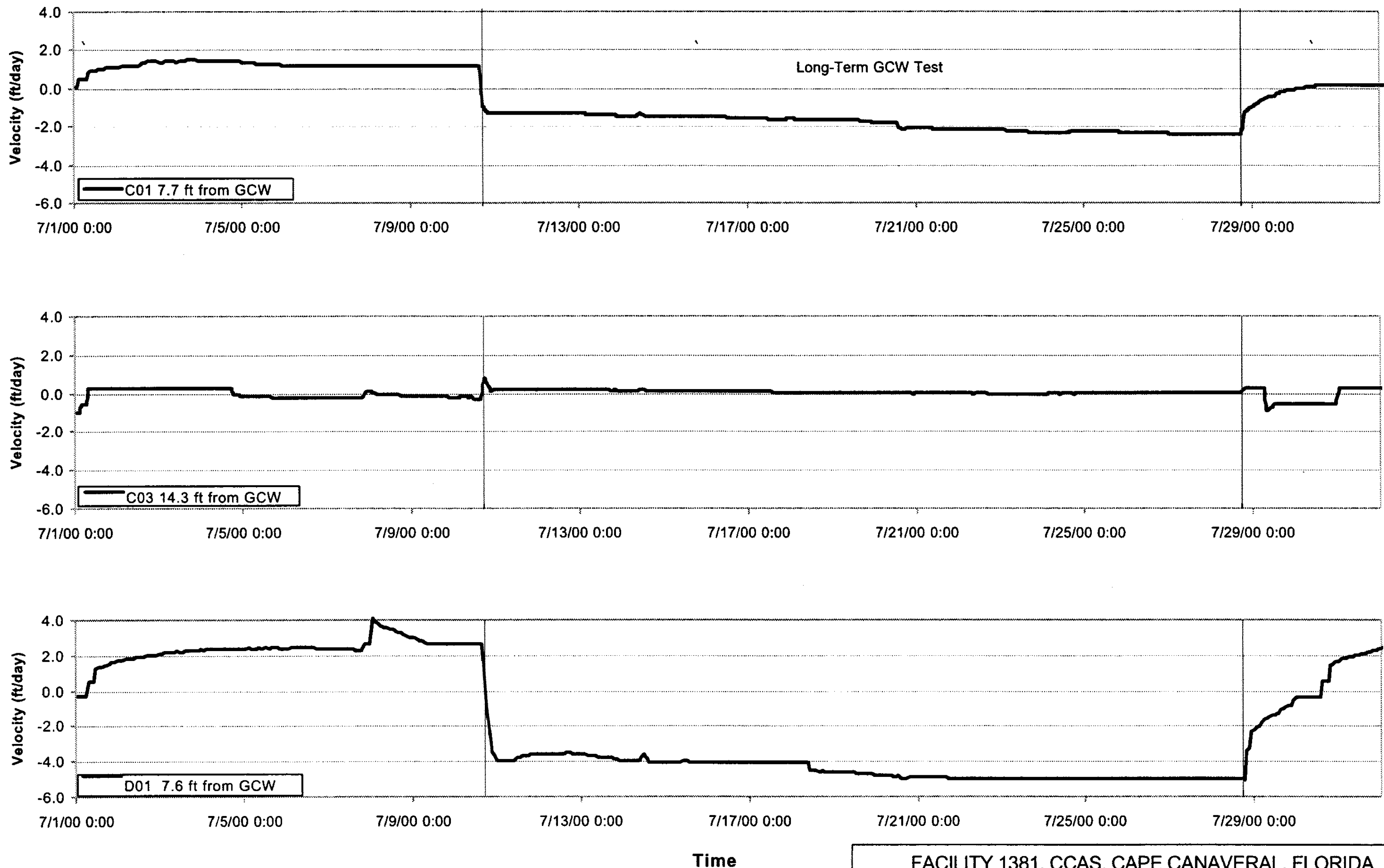


NOTES:
1) Data shown is from a long term GCW circulation test conducted by Parsons in July 2000.
2) Positive vertical velocity is indicative of upward hydraulic gradient.
3) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 22
Vertical Groundwater Darcy Velocity Versus Time in Shallow Aquifer Zone Measured by Flow Sensors 7/1/00 - 7/31/00 (Actual Data)

Tetra Tech EM Inc.



NOTES:

1) Data shown is from a long term GCW circulation test conducted by Parsons in July 2000.

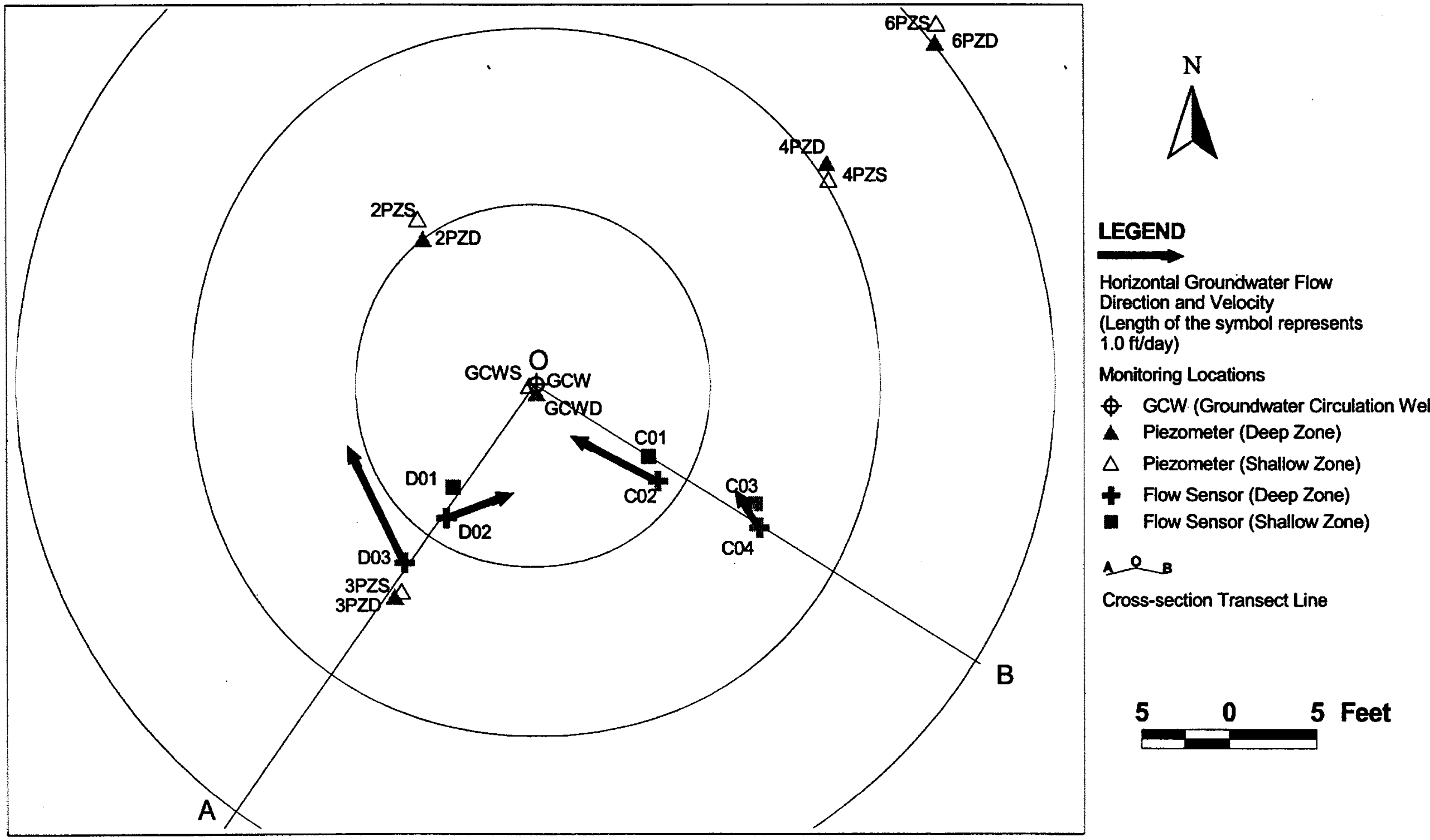
2) Positive vertical velocity is indicative of upward hydraulic gradient.

3) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 23
Vertical Groundwater Darcy Velocity Versus Time in Shallow Aquifer Zone Measured by Flow Sensors 7/1/00 - 7/31/00 (Data with Background Removed)

Tetra Tech EM Inc.



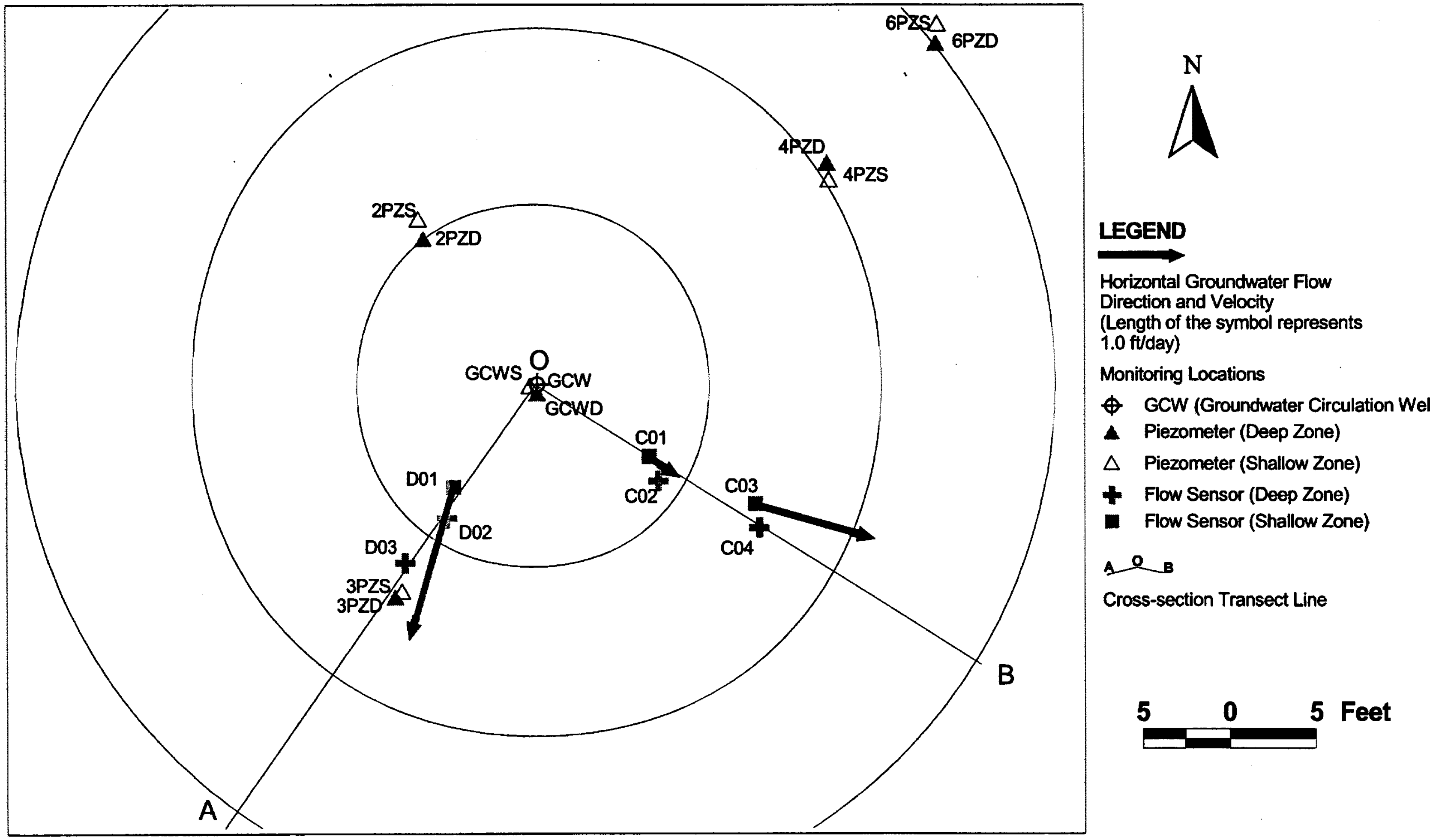
Resultant Data

NOTES:
1) Data evaluated was collected on July 28, 2000
2) Flow sensor data shown is from long-term GCW circulation test conducted by Parsons in July 2000.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 24
Horizontal Groundwater Darcy Velocity in Deep Aquifer Zone Measured by Flow Sensors Under Recirculation Conditions (07/28/00)

Tetra Tech EM Inc.



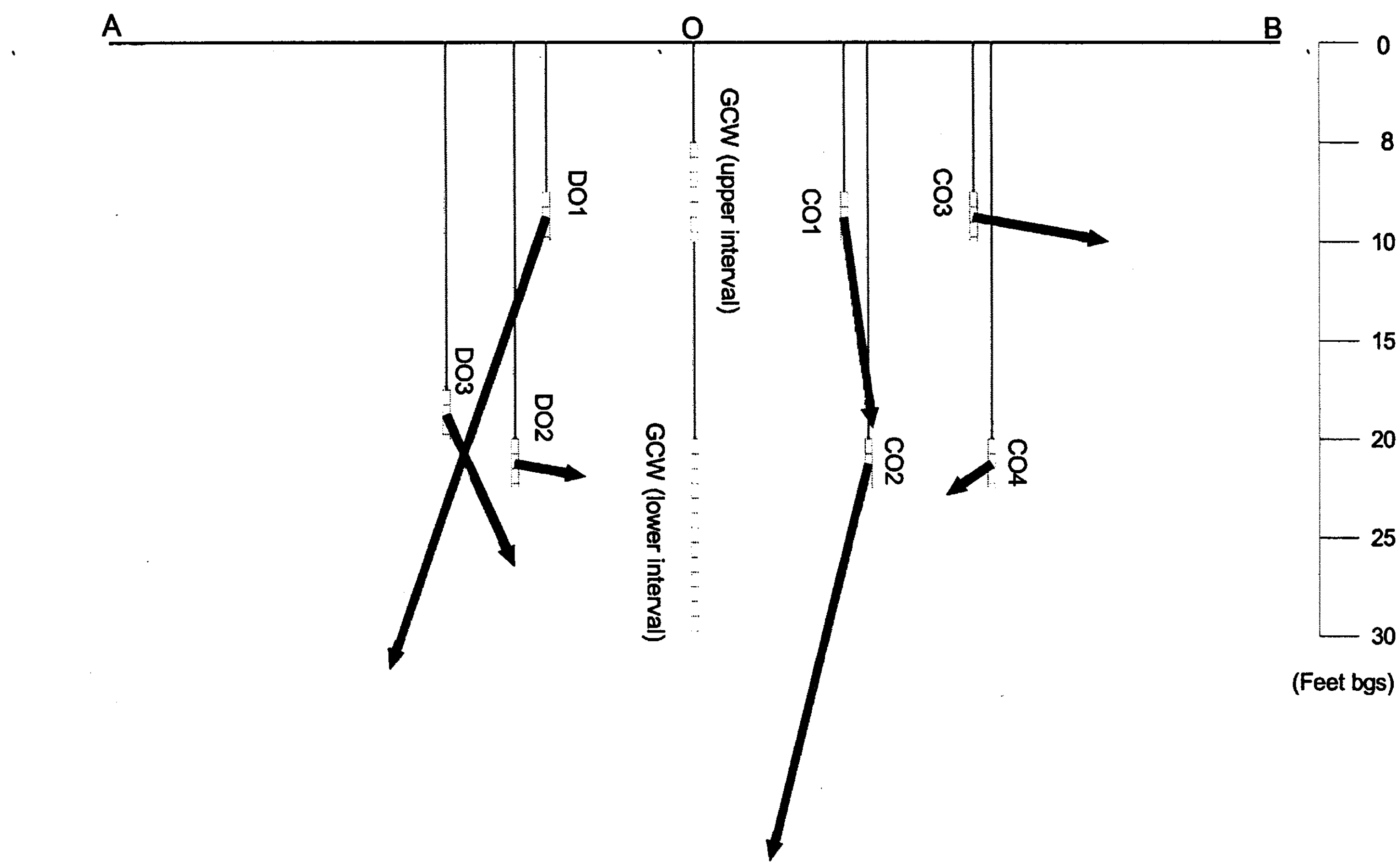
Resultant Data

NOTES:
1) Data evaluated was collected on July 28, 2000
2) Flow sensor data shown is from long-term GCW circulation test conducted by Parsons in July 2000.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 25
Horizontal Groundwater Darcy Velocity in Shallow Aquifer Zone Measured by Flow Sensors Under Recirculation Conditions (07/28/00)

Tetra Tech EM Inc.



LEGEND

Groundwater Flow Direction and Velocity
(Length of the symbol represents 1.0 ft/day)

Flow Sensor Interval and GCW Screened Interval

5 0 5 Feet

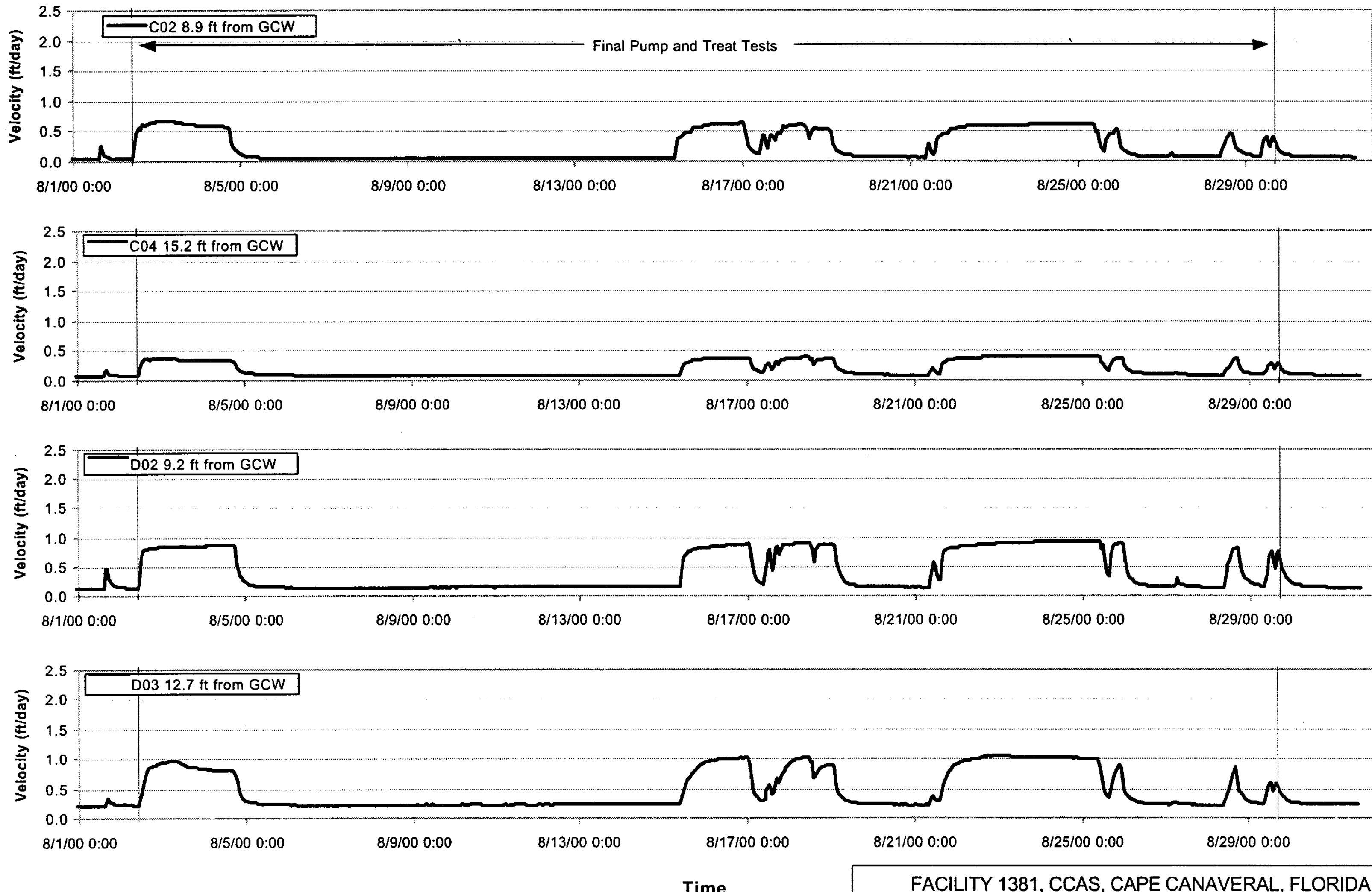
Resultant Data

NOTES:
1) Data evaluated was collected on July 28, 2000.
2) Flow sensor shown is from long-term GCW circulation test conducted bu Parsons in July 2000.
3) Cross-section transect line location is shown on Figure 3.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 26
Resultant Groundwater Flow Velocity Projected onto Cross-Section AOB Under Recirculation Conditions (7/28/00)

Tetra Tech EM Inc.

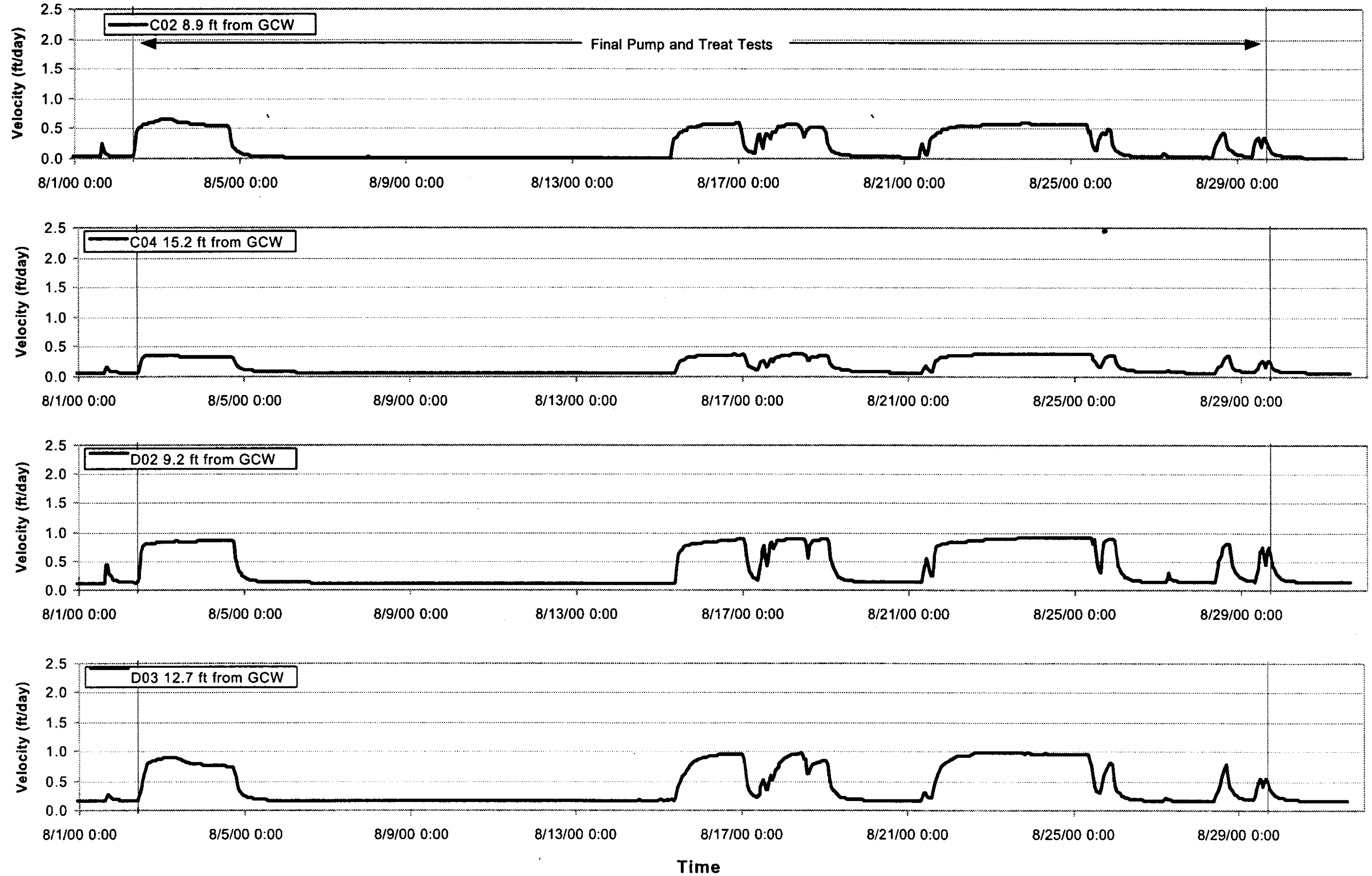


NOTES:
1) Data shown is from final pumping-and-treat testing conducted by Parsons in August 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 27
Horizontal Groundwater Darcy Velocity Versus Time in Deep Aquifer Zone Measured by Flow Sensors 8/1/00 - 8/31/00 (Actual Data)

Tetra Tech EM Inc.

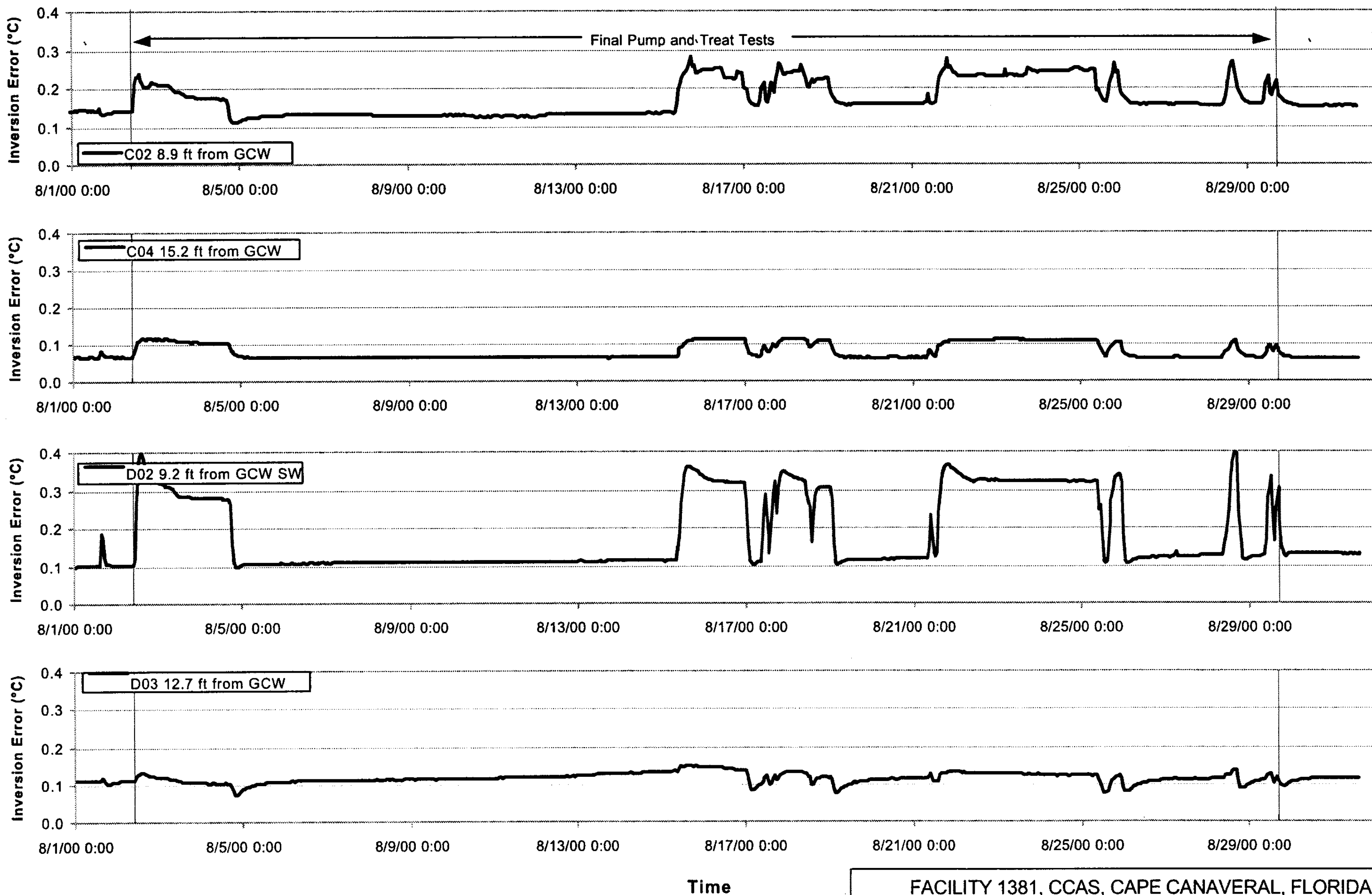


NOTES:
1) Data shown is from final pumping-and-treat testing conducted by Parsons in August 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 28
Horizontal Groundwater Darcy Velocity Versus Time in Deep Aquifer Zone Measured by Flow Sensors 8/1/00 - 8/31/00 (Data with Background Removed)

Tetra Tech EM Inc.

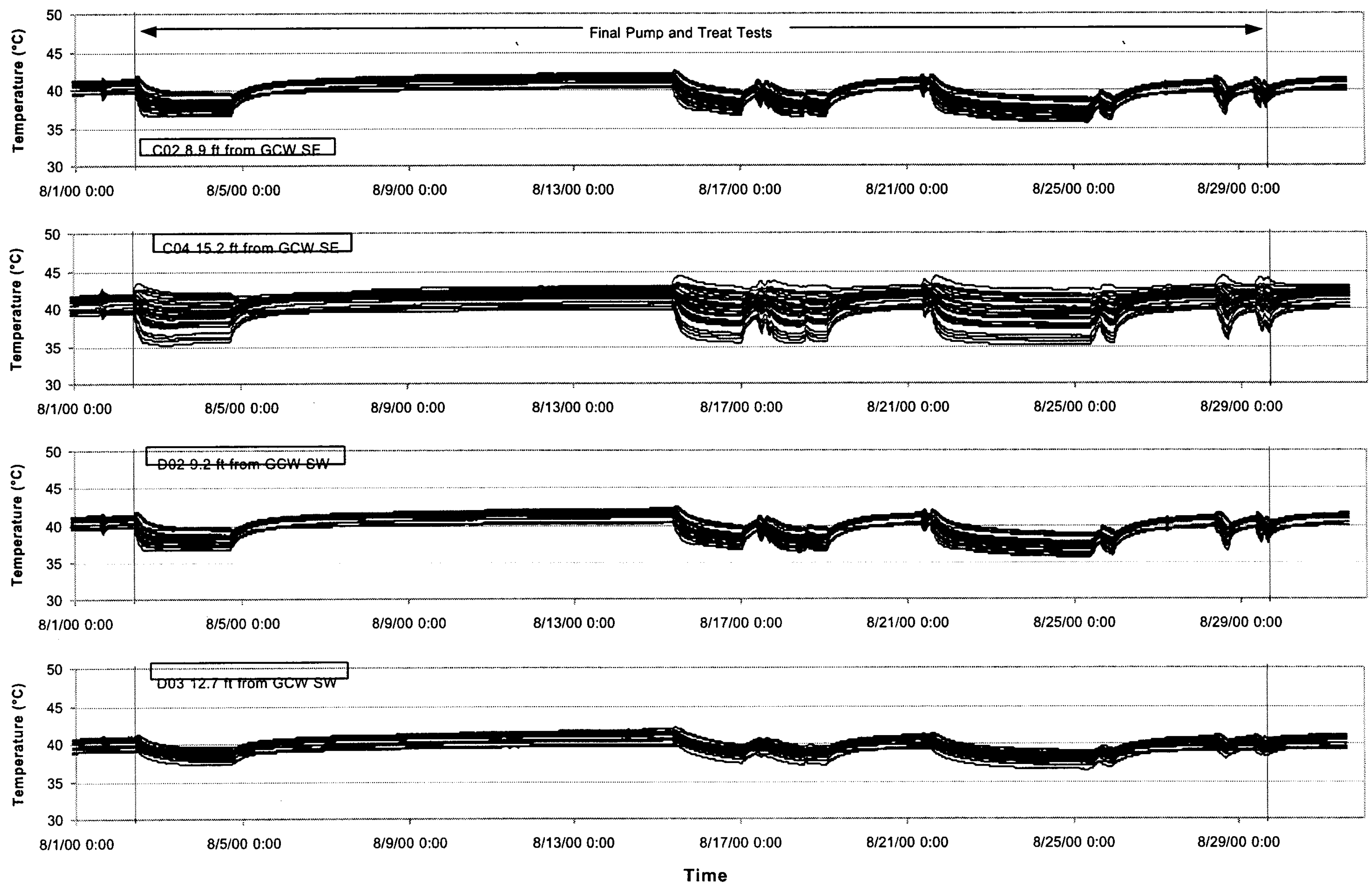


NOTES:
1) Data shown is from final pumping-and-treat testing conducted by Parsons in August 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 29
Flow Sensor Inversion Errors Versus Time in Deep Aquifer Zone
8/1/00 - 8/31/00

Tetra Tech EM Inc.



NOTES:

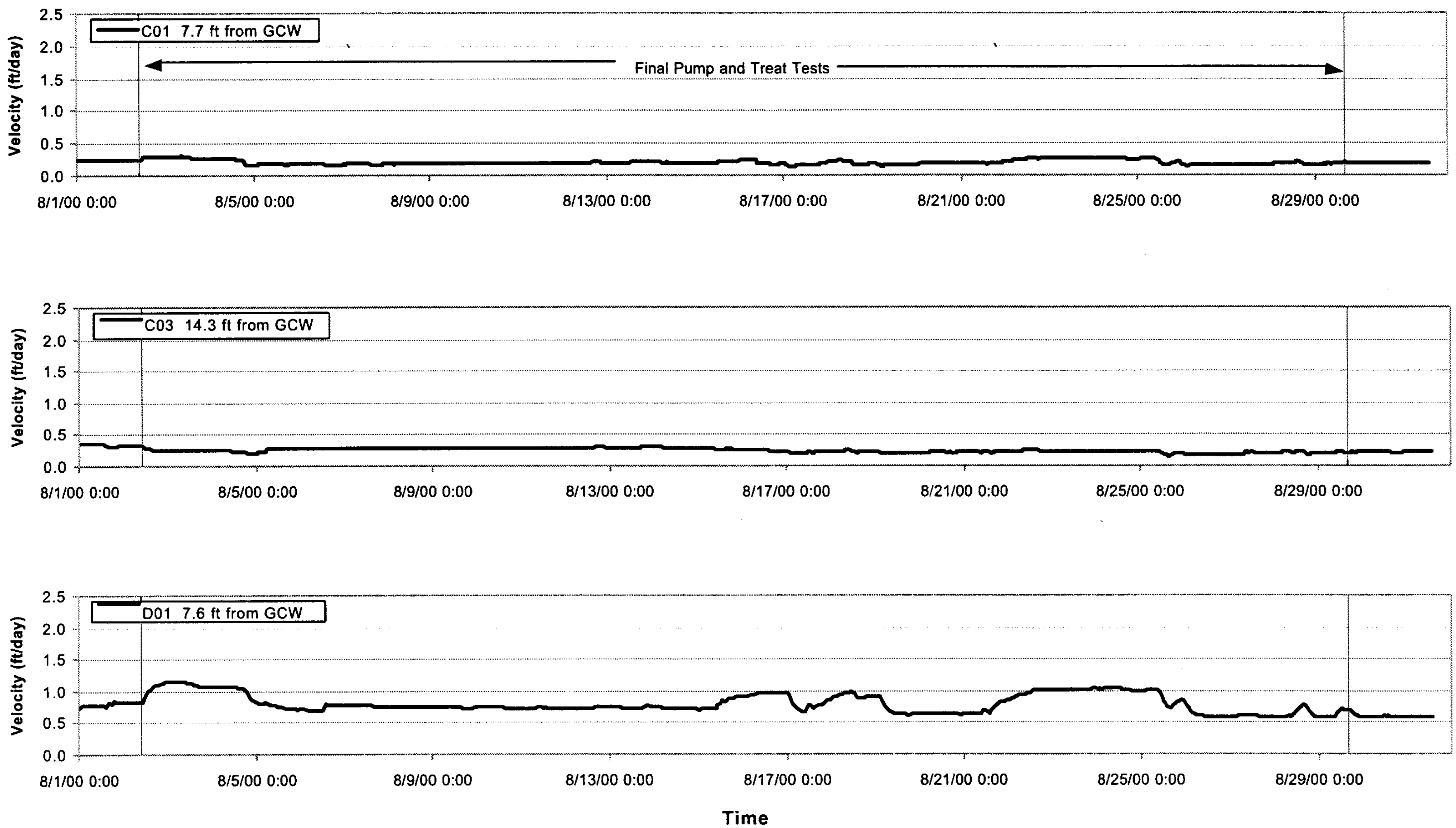
1) Data shown is from final pumping-and-treat testing conducted by Parsons in August 2000.

2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 30
Thermistor Temperature Versus Time in Deep Aquifer Zone Flow Sensors
8/1/00 - 8/31/00

Tetra Tech EM Inc.

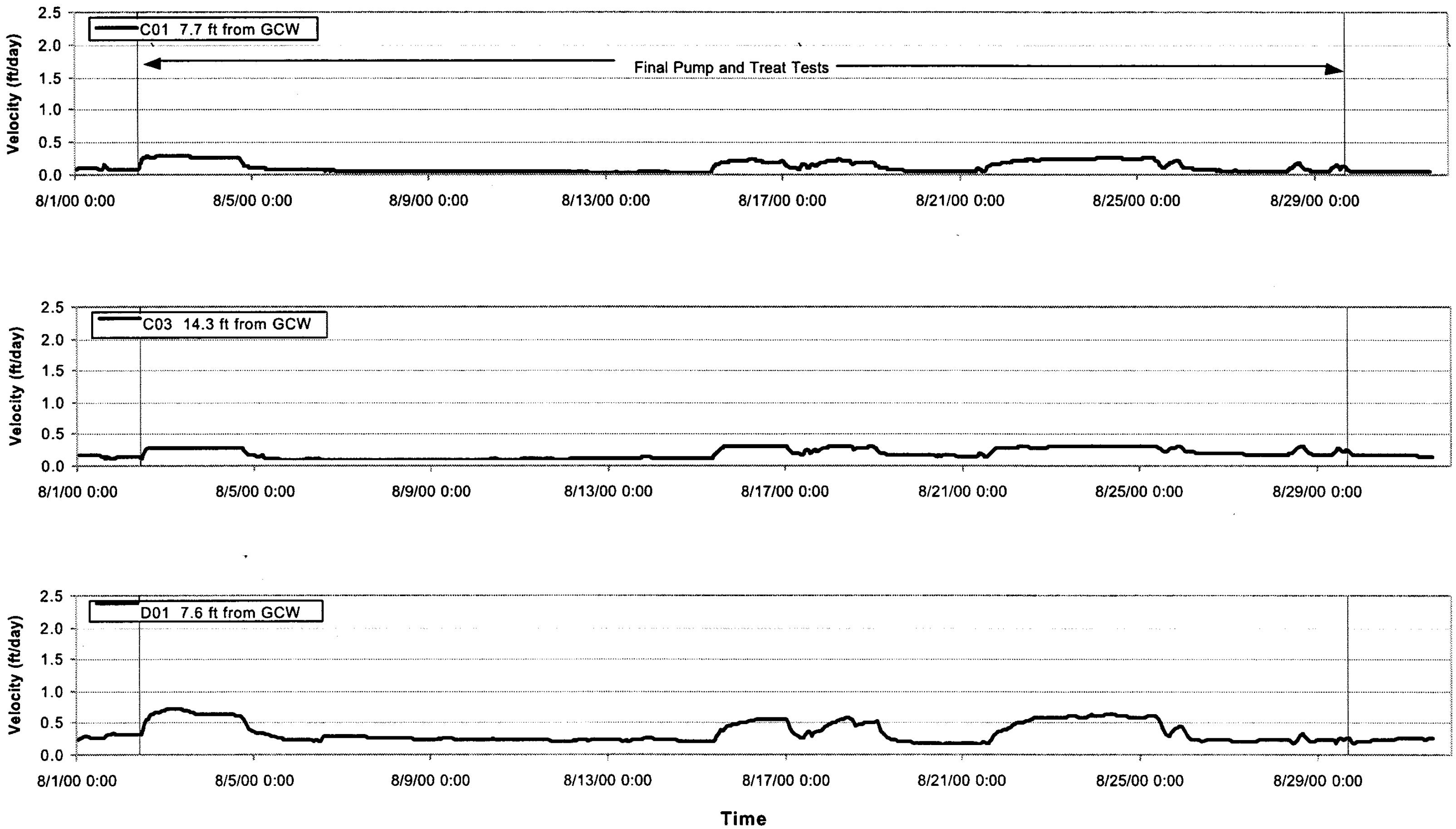


NOTES:
1) Data shown is from final pumping-and-treat testing conducted by Parsons in August 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 31
Horizontal Groundwater Darcy Velocity Versus Time in Shallow Aquifer Zone Measured by Flow Sensors 8/1/00 - 8/31/00 (Actual Data)

Tetra Tech EM Inc.

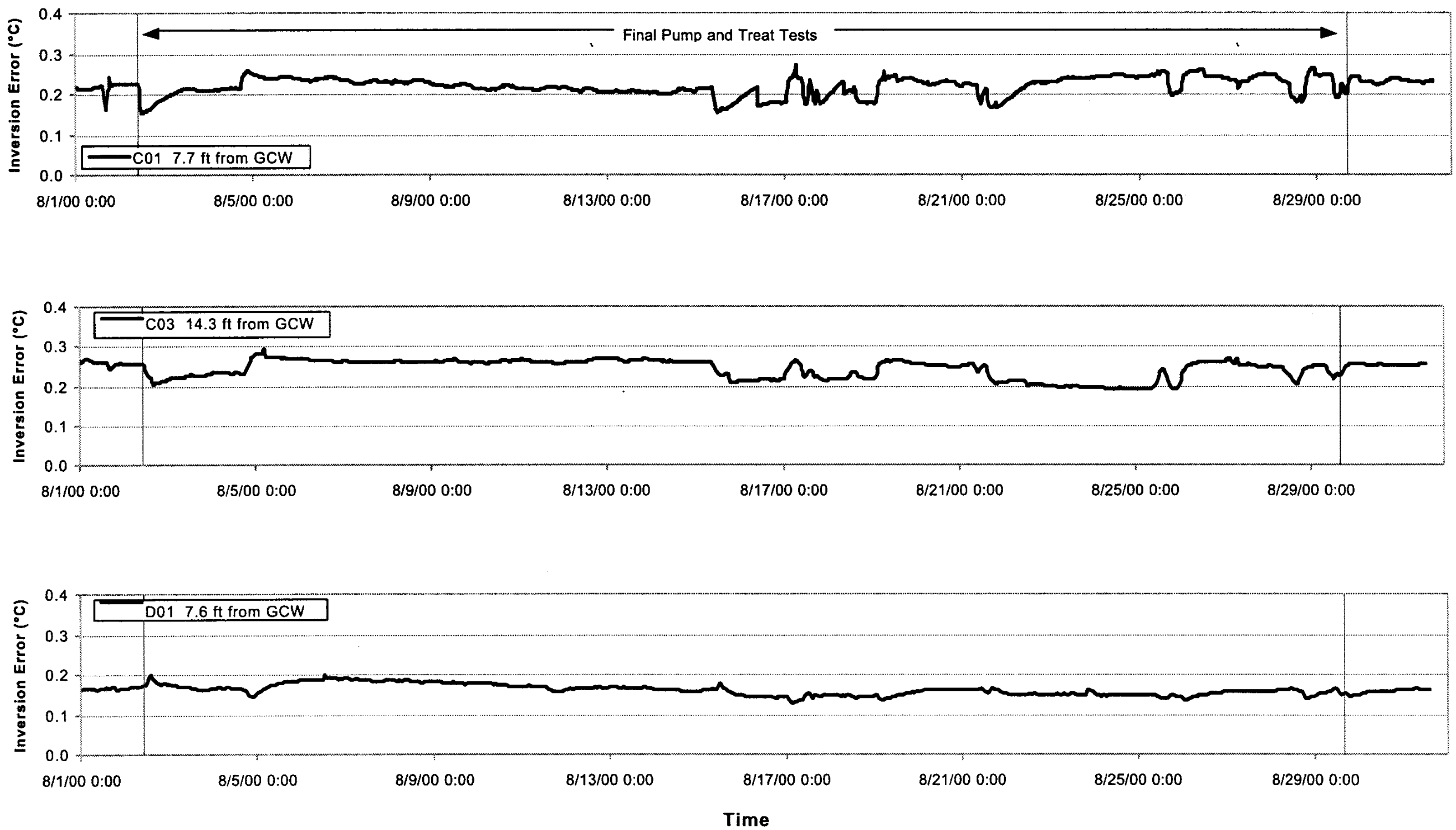


NOTES:
1) Data shown is from final pumping-and-treat testing conducted by Parsons in August 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 32
Horizontal Groundwater Darcy Velocity Versus Time in Shallow Aquifer Zone Measured by Flow Sensors 8/1/00 - 8/31/00 (Data with Background Removed)

Tetra Tech EM Inc.

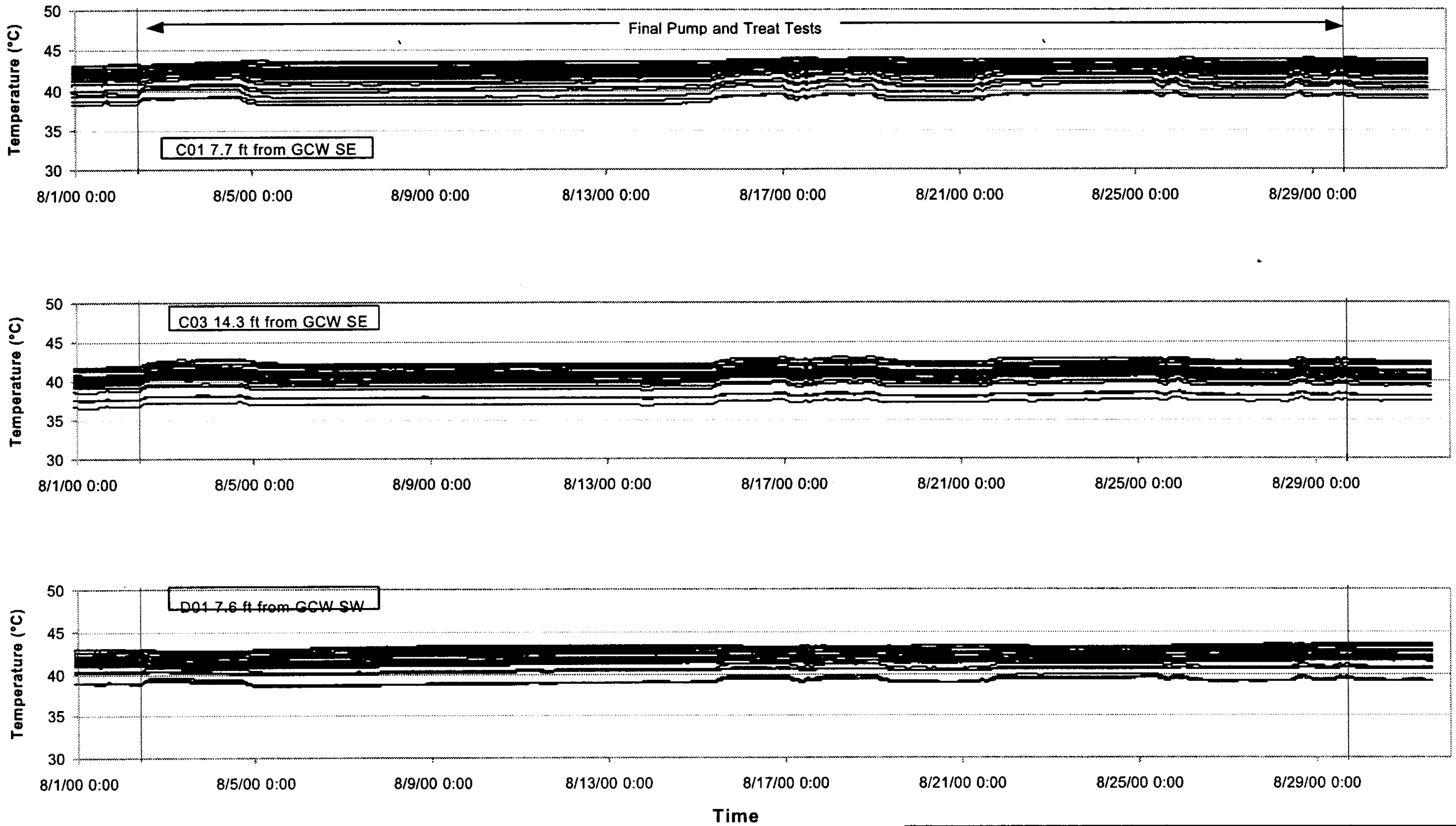


NOTES:
1) Data shown is from final pumping-and-treat testing conducted by Parsons in August 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 33
Flow Sensor Inversion Errors Versus Time in Shallow Aquifer Zone
8/1/00 - 8/31/00

Tetra Tech EM Inc.

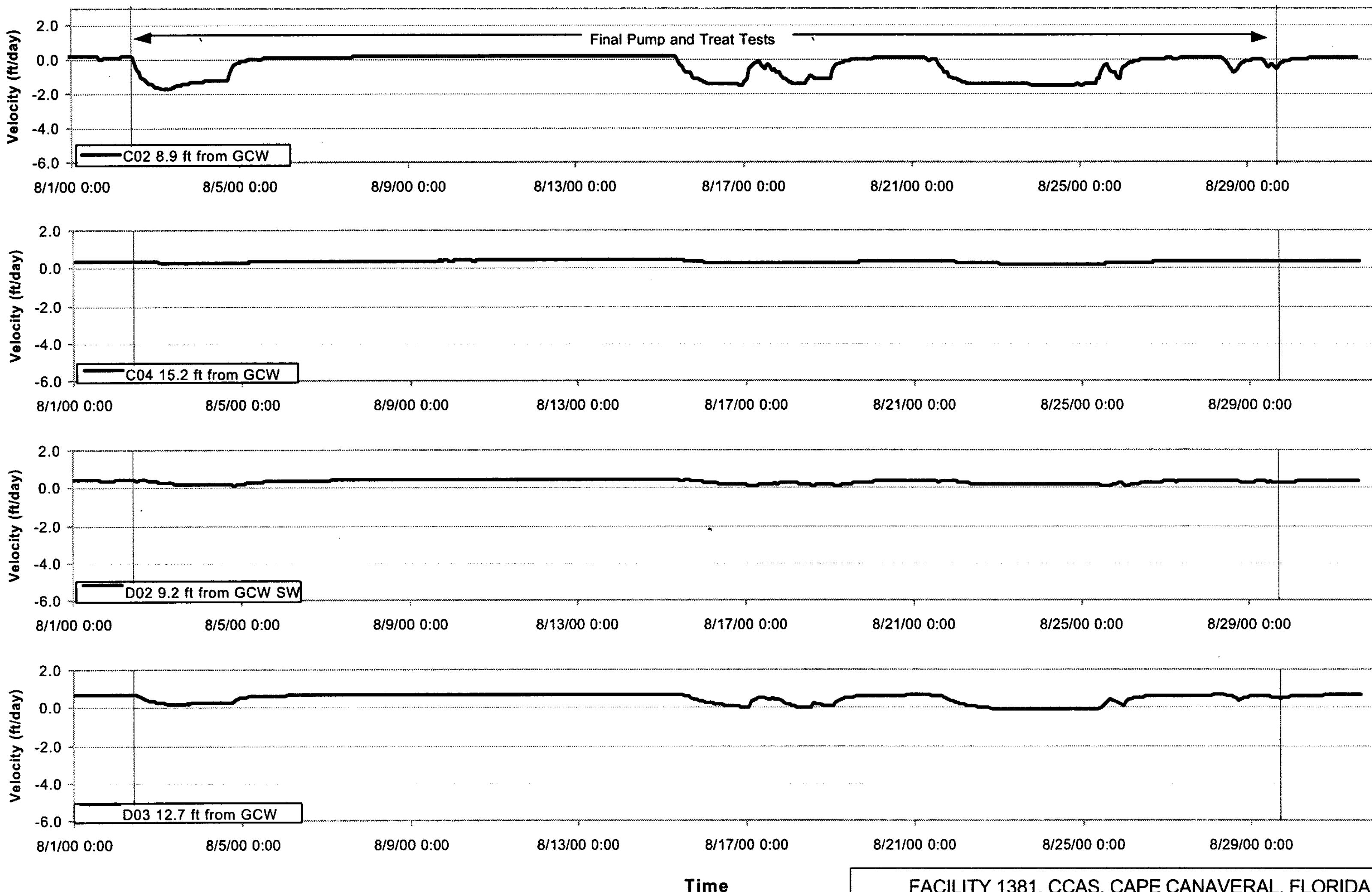


NOTES:
1) Data shown is from final pumping-and-treat testing conducted by Parsons in August 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 34
Thermistor Temperature Versus Time in Shallow Aquifer Zone Flow Sensors
8/1/00 - 8/31/00

Tetra Tech EM Inc.

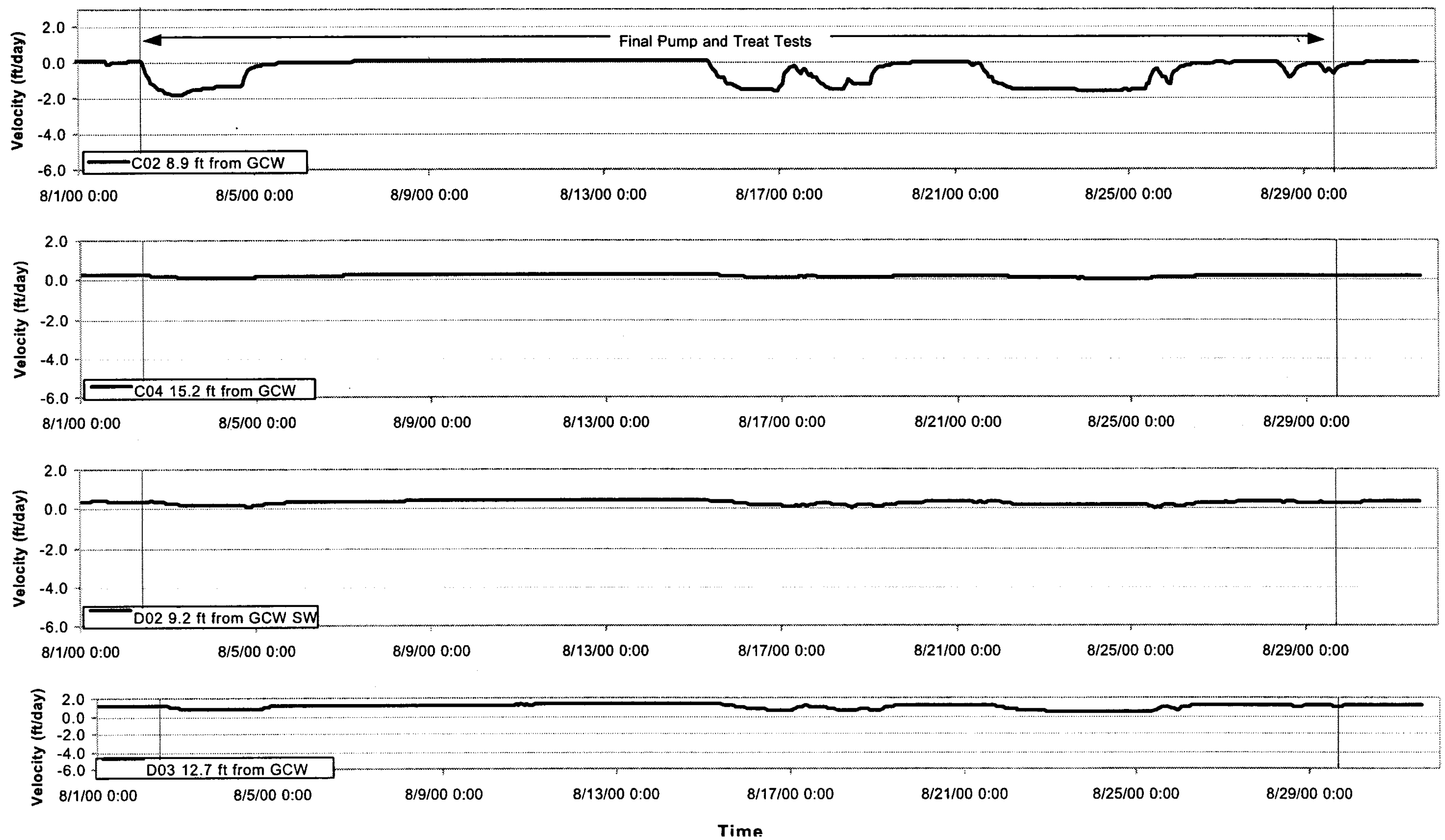


NOTES:
1) Data shown is from final pumping-and-treat testing conducted by Parsons in August 2000.
2) Positive vertical velocity is indicative of upward hydraulic gradient.
3) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 35
Vertical Groundwater Darcy Velocity Versus Time in Deep Aquifer Zone Measured by Flow Sensors 8/1/00 - 8/31/00 (Actual Data)

Tetra Tech EM Inc.

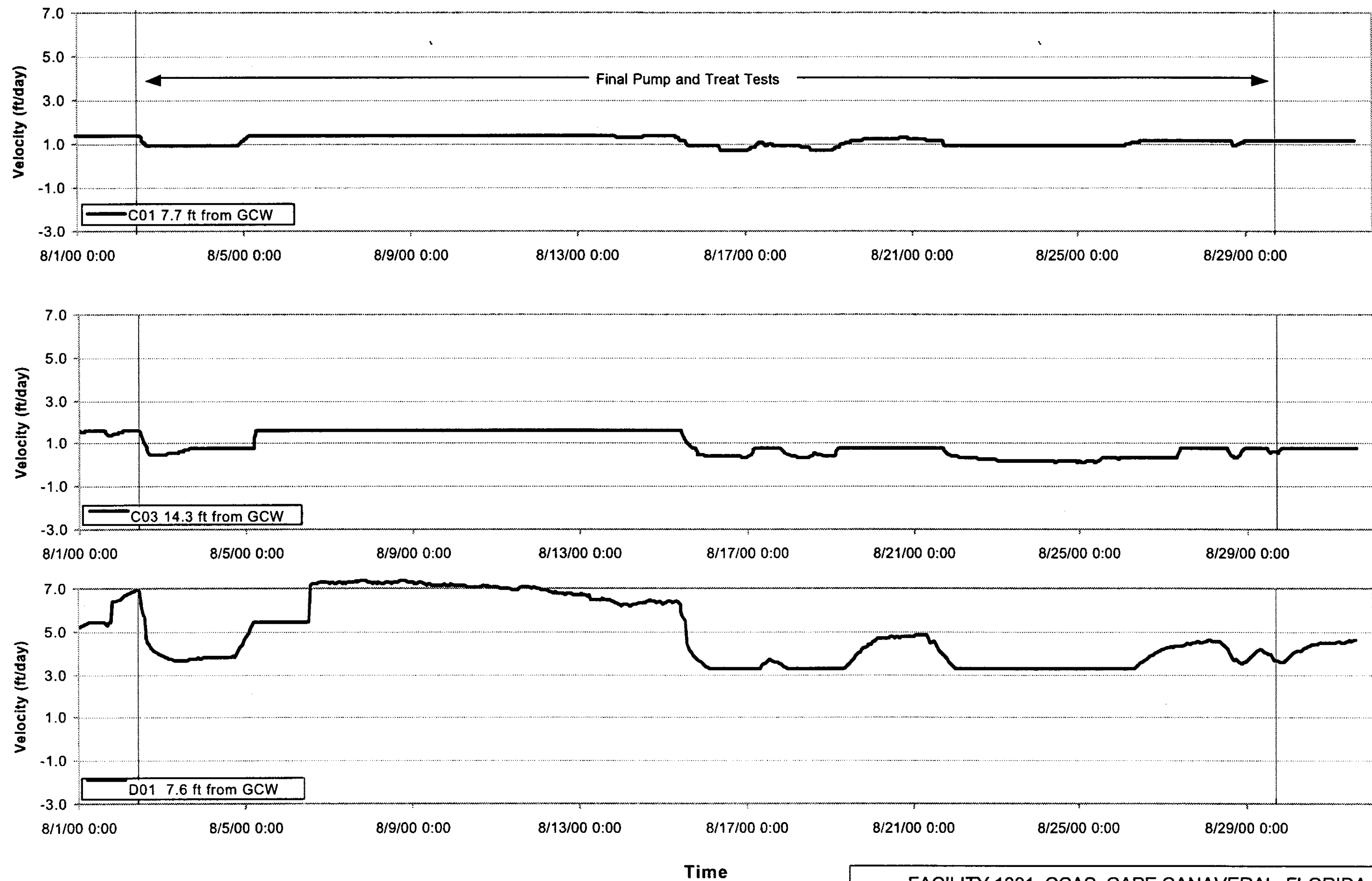


NOTES:
1) Data shown is from final pumping-and-treat testing conducted by Parsons in August 2000.
2) Positive vertical velocity is indicative of upward hydraulic gradient.
3) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 36
Vertical Groundwater Darcy Velocity Versus Time in Deep Aquifer Zone Measured by Flow Sensors 8/1/00 - 8/31/00 (Data with Background Removed)

Tetra Tech EM Inc.

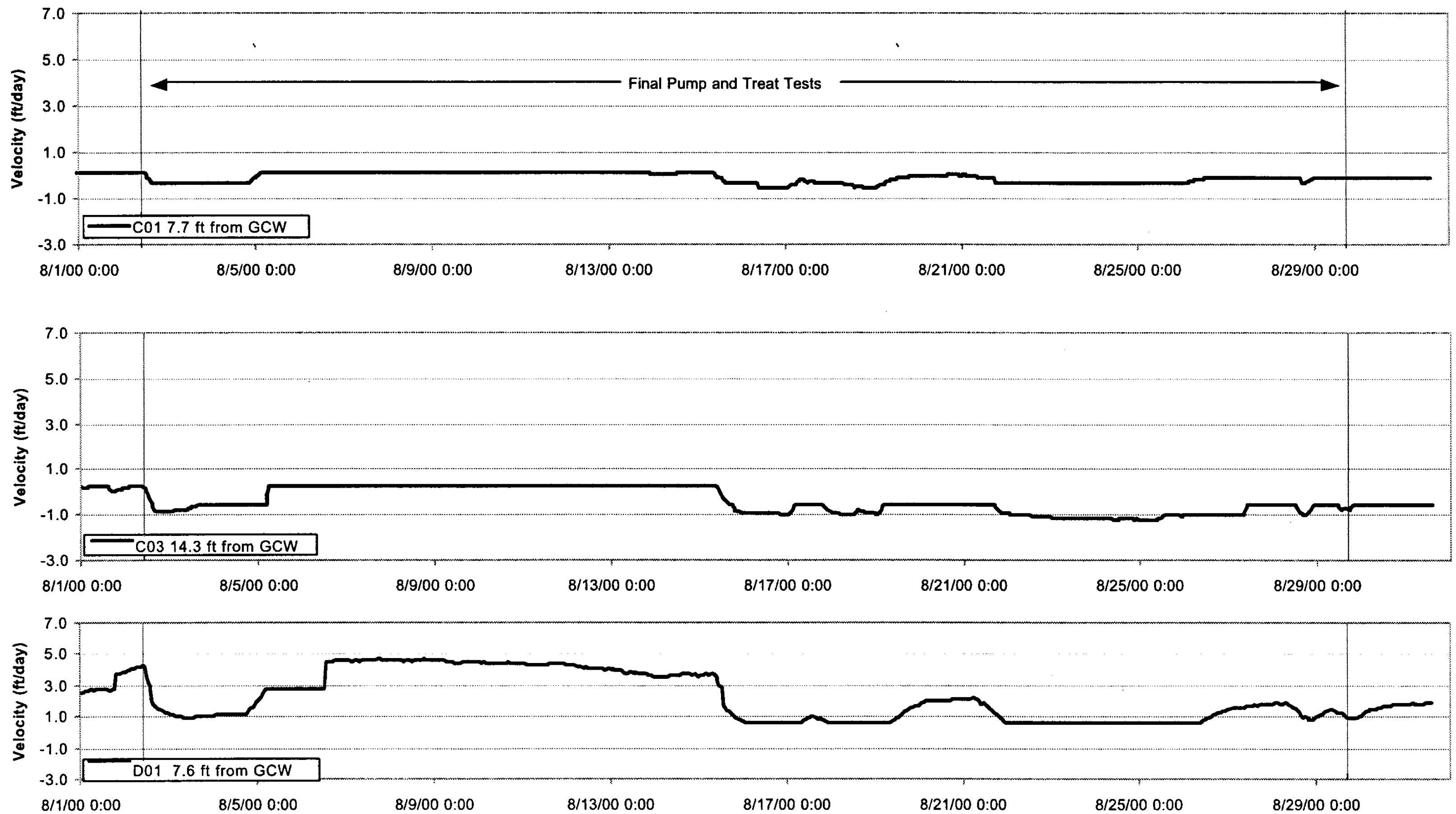


NOTES:
1) Data shown is from final pumping-and-treat testing conducted by Parsons in August 2000.
2) Positive vertical velocity is indicative of upward hydraulic gradient.
3) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 37
Vertical Groundwater Darcy Velocity Versus Time in Shallow Aquifer Zone Measured by Flow Sensors 8/1/00 - 8/31/00 (Actual Data)

Tetra Tech EM Inc.

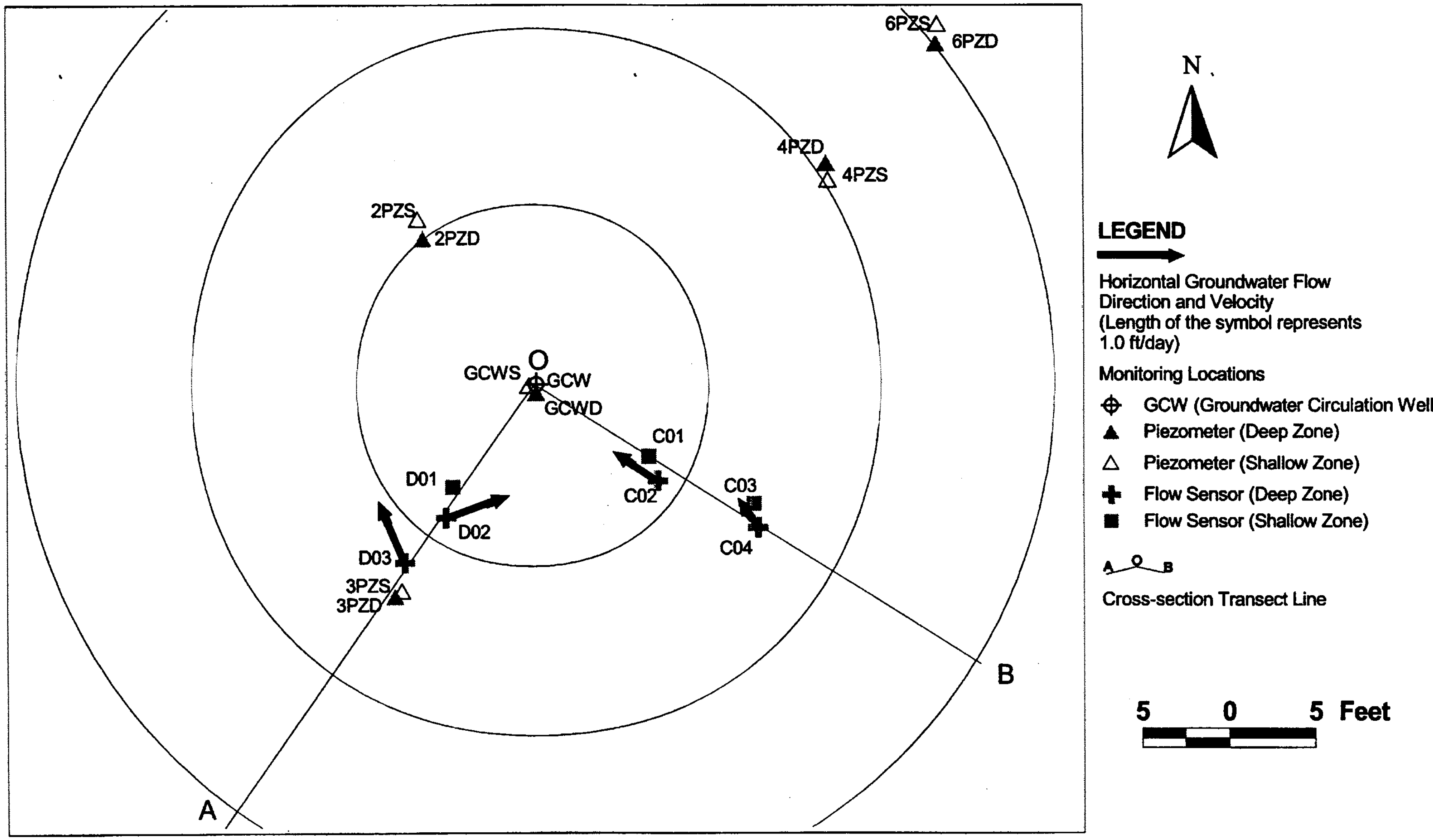


NOTES:
1) Data shown is from final pumping-and-treat testing conducted by Parsons in August 2000.
2) Positive vertical velocity is indicative of upward hydraulic gradient.
3) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 38
Vertical Groundwater Darcy Velocity Versus Time in Shallow Aquifer Zone Measured by Flow Sensors 8/1/00 - 8/31/00 (Data with Background Removed)

Tetra Tech EM Inc.



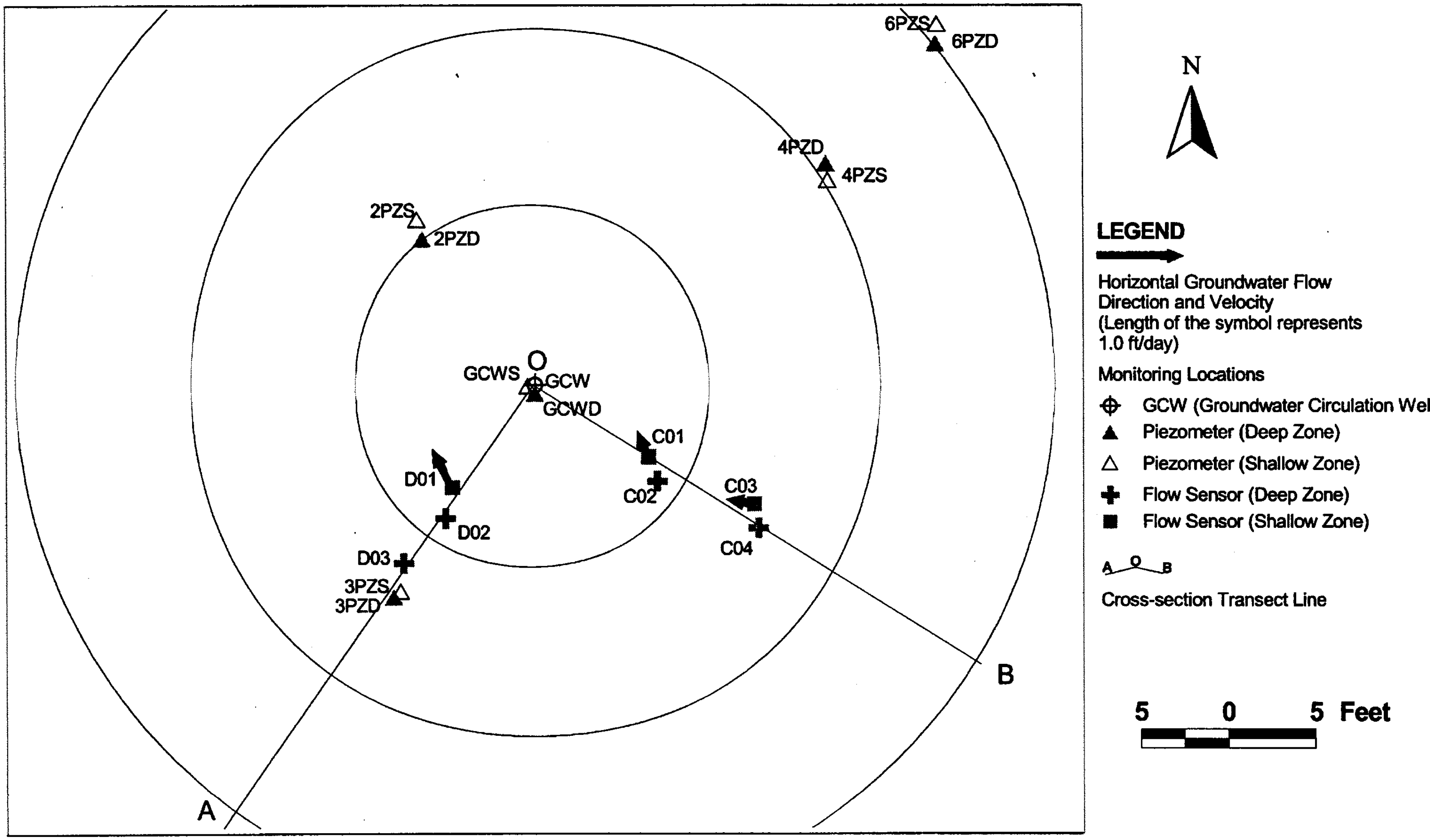
Resultant Data

NOTES:
1) Data evaluated was collected on August 25, 2000.
2) Flow sensor data shown is from pump-and-treat testing conducted by Parsons in August 2000.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 39
Horizontal Groundwater Darcy Velocity in Deep Aquifer Zone Measured by Flow Sensors Under Pumping Conditions (08/25/00)

Tetra Tech EM Inc.



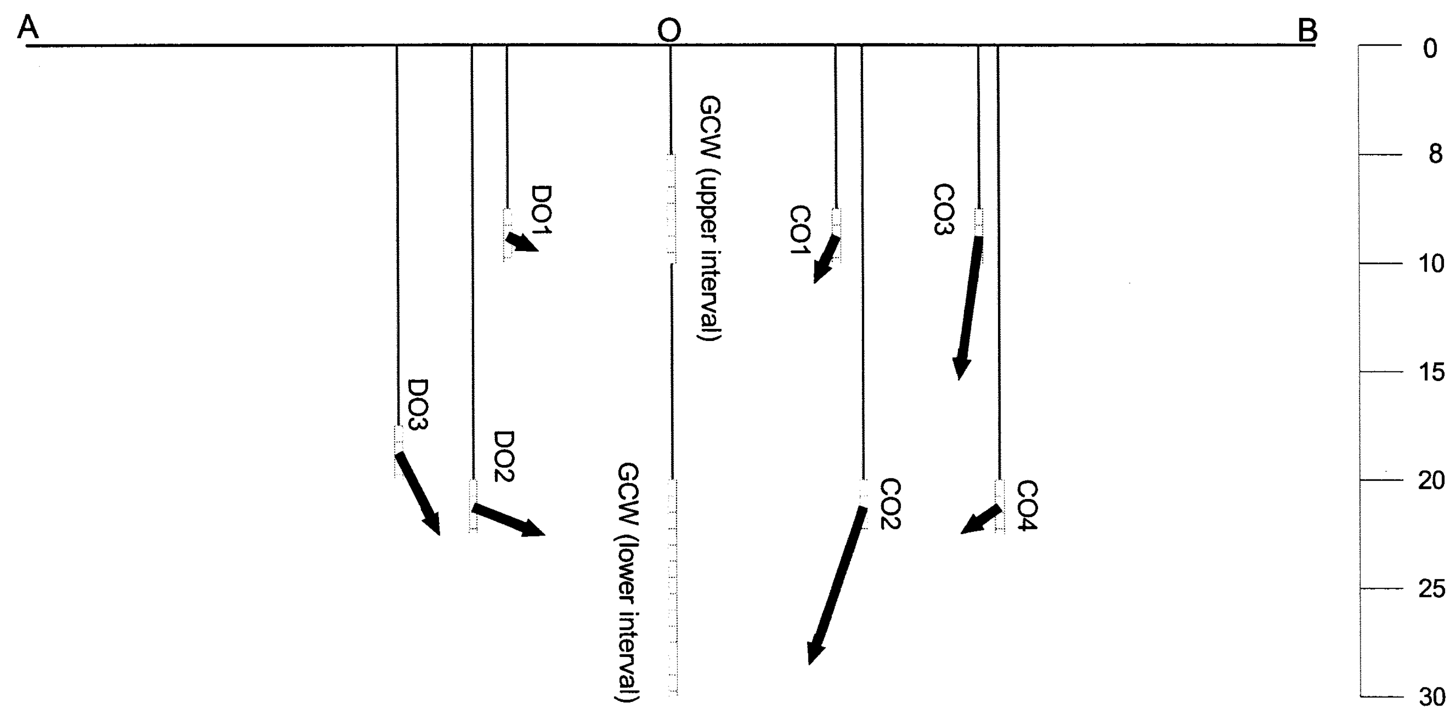
Resultant Data

NOTES:
1) Data evaluated was collected on August 25, 2000.
2) Flow sensor data shown is from pump-and-treat testing conducted by Parsons in August 2000.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 40
Horizontal Groundwater Darcy Velocity in Shallow Aquifer Zone Measured by Flow Sensors Under Pumping Conditions (08/25/00)

Tetra Tech EM Inc.



LEGEND

Groundwater Flow Direction and Velocity
(Length of the symbol represents 1.0 ft/day)

Flow Sensor Interval and GCW Screened Interval

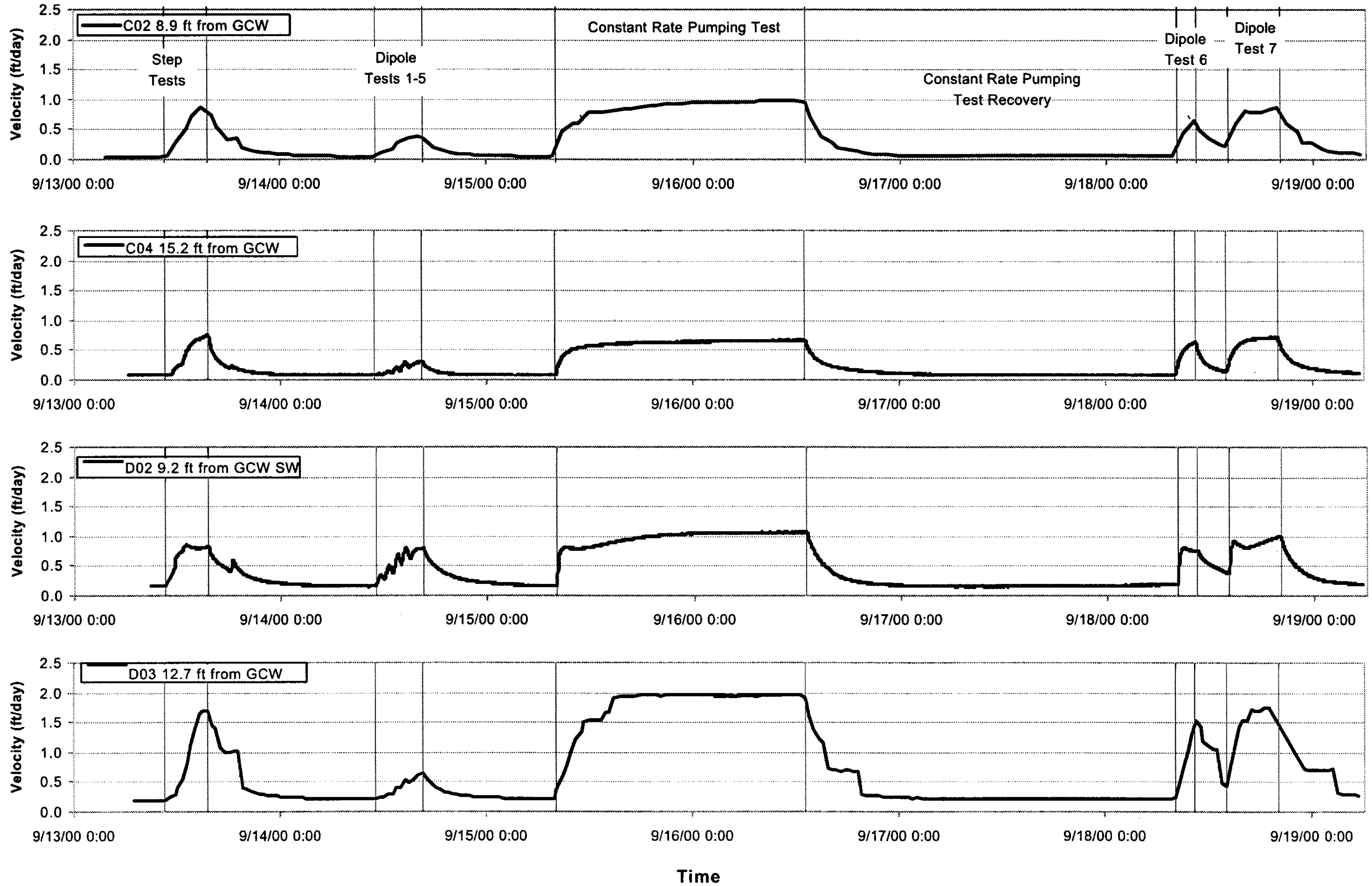
5 0 5 Feet

NOTES:
1) Data evaluated was collected on August 25, 2000.
2) Flow sensor data shown is from pump-and-treat testing conducted by Parsons in August 2000.
3) Cross-section transect line location is shown on Figure 3.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 41
Resultant Groundwater Flow Velocity Projected onto Cross-Section AOB Under Pumping Conditions (08/25/00)

Tetra Tech EM Inc.

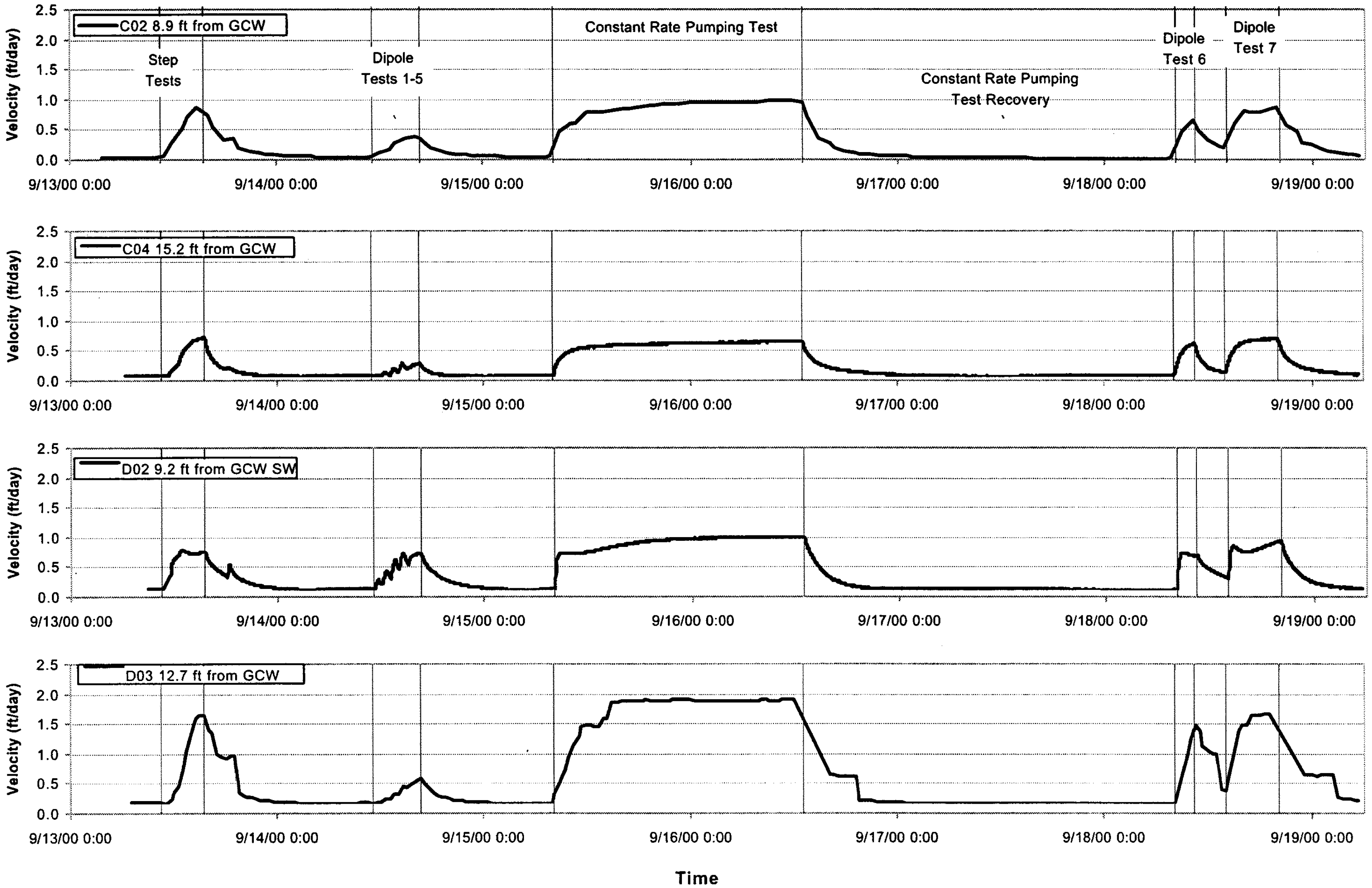


NOTES:
1) Aquifer testing period was from September 13 to 19, 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 42
Horizontal Groundwater Darcy Velocity Versus Time in Deep Aquifer Zone Measured by Flow Sensors During Aquifer Testing Period (Actual Data)

Tetra Tech EM Inc.

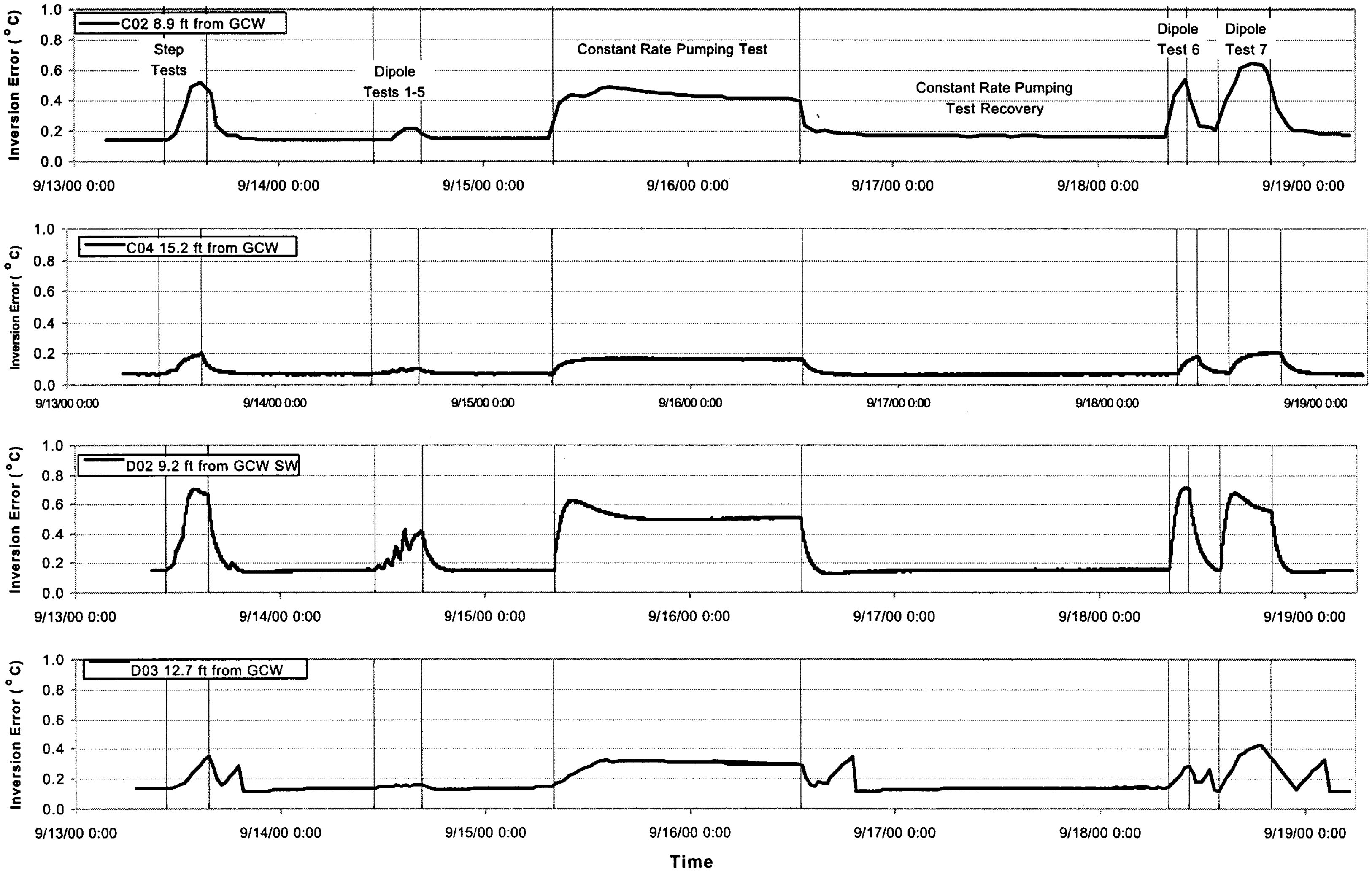


NOTES:
1) Aquifer testing period was from September 13 to 19, 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 43
Horizontal Groundwater Darcy Velocity Versus Time in Deep Aquifer Zone Measured by Flow Sensors During Aquifer Testing Period (Data with Background Removed)

Tetra Tech EM Inc.

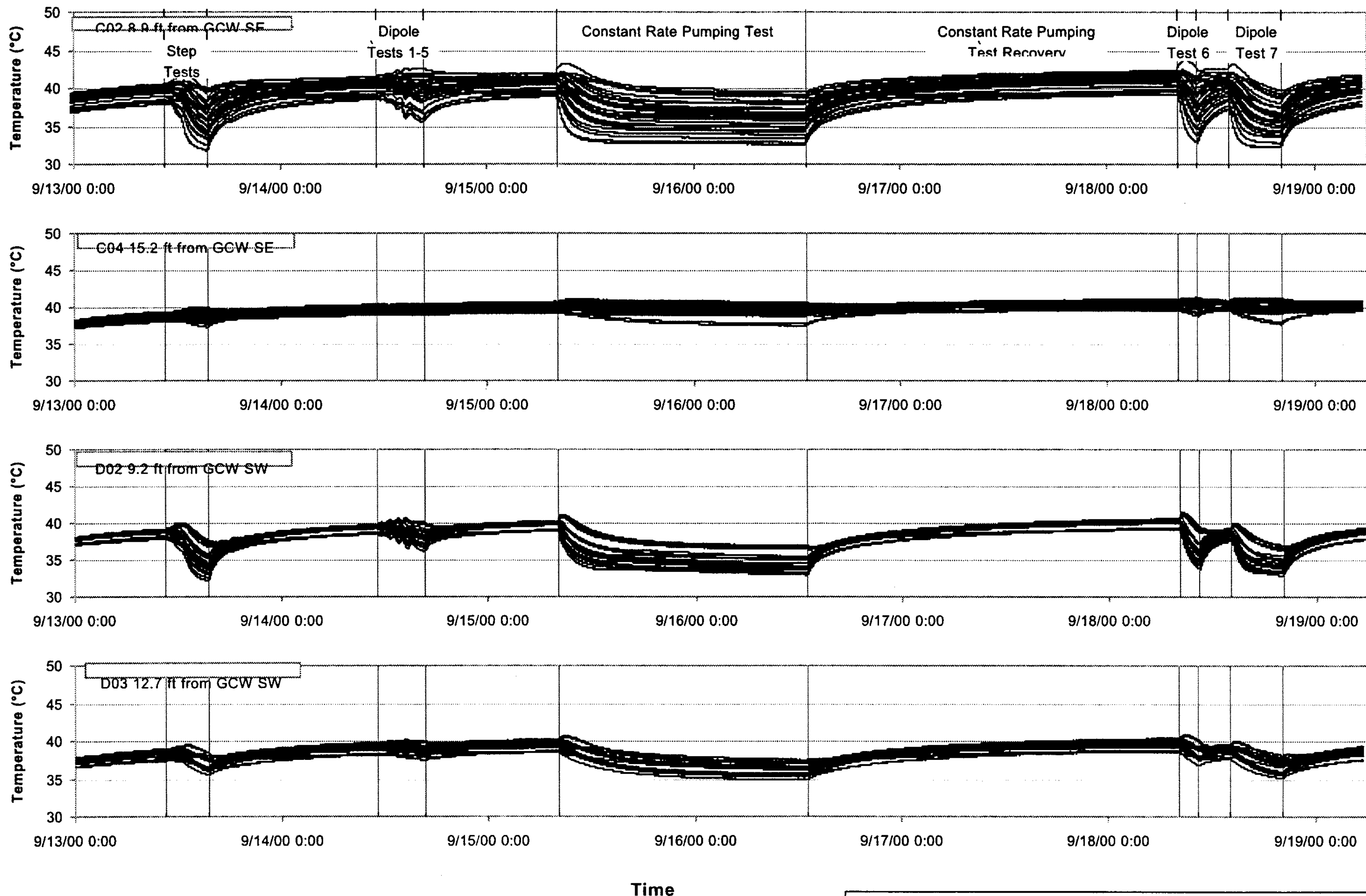


NOTES:
1) Aquifer testing period was from September 13 to 19, 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 44
Inversion Error Versus Time in Deep Aquifer Zone Flow Sensors During Aquifer Testing Period

Tetra Tech EM Inc.

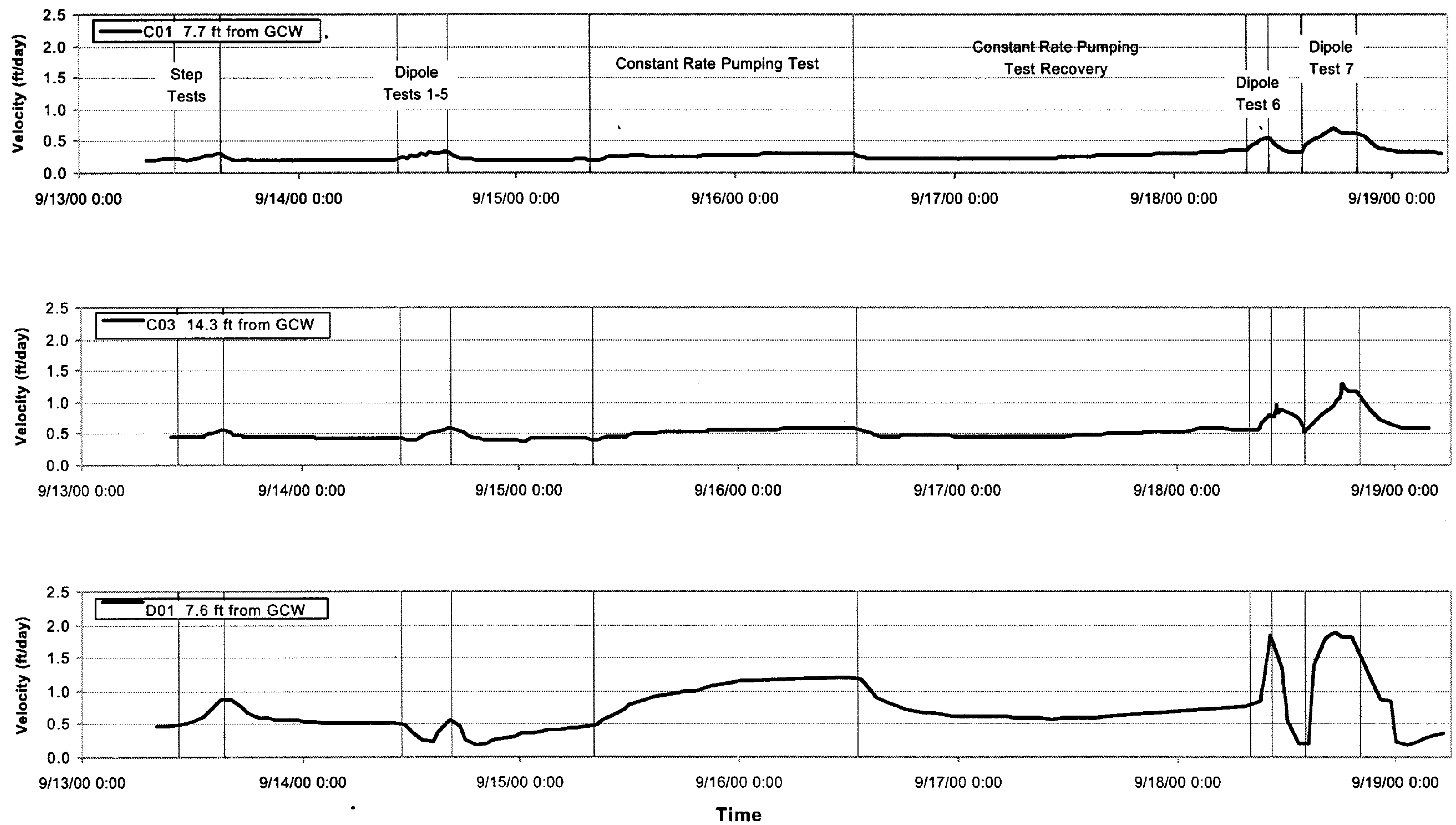


NOTES:
1) Aquifer testing period was from September 13 to 19, 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 45
Thermistor Temperature Versus Time in Deep Aquifer Zone Flow Sensors During Aquifer Testing Period

Tetra Tech EM Inc.

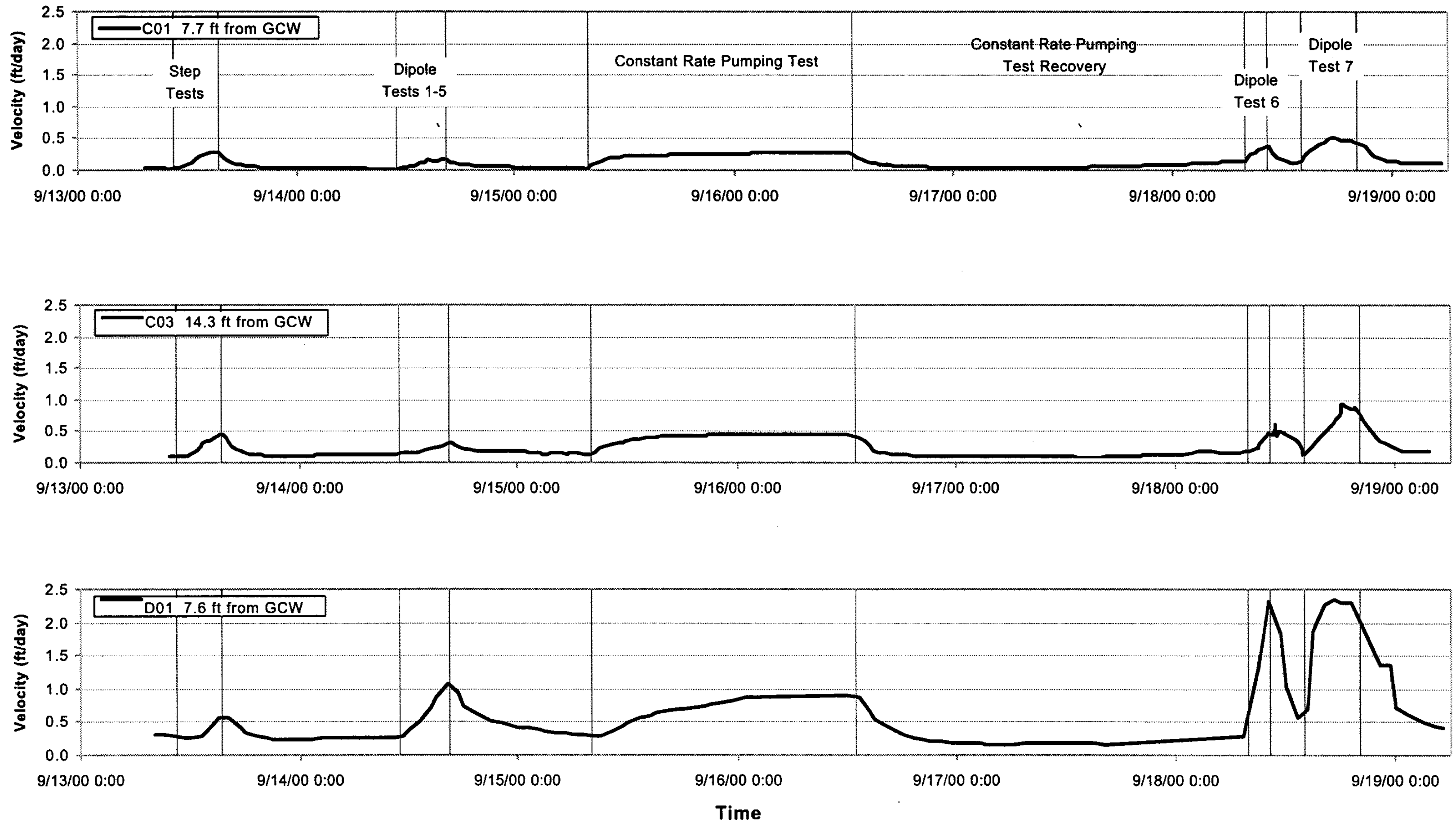


NOTES:
1) Aquifer testing period was from September 13 to 19, 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 46
Horizontal Groundwater Darcy Velocity Versus Time in Shallow Aquifer Zone Measured by Flow Sensors During Aquifer Testing Period (Actual Data)

Tetra Tech EM Inc.

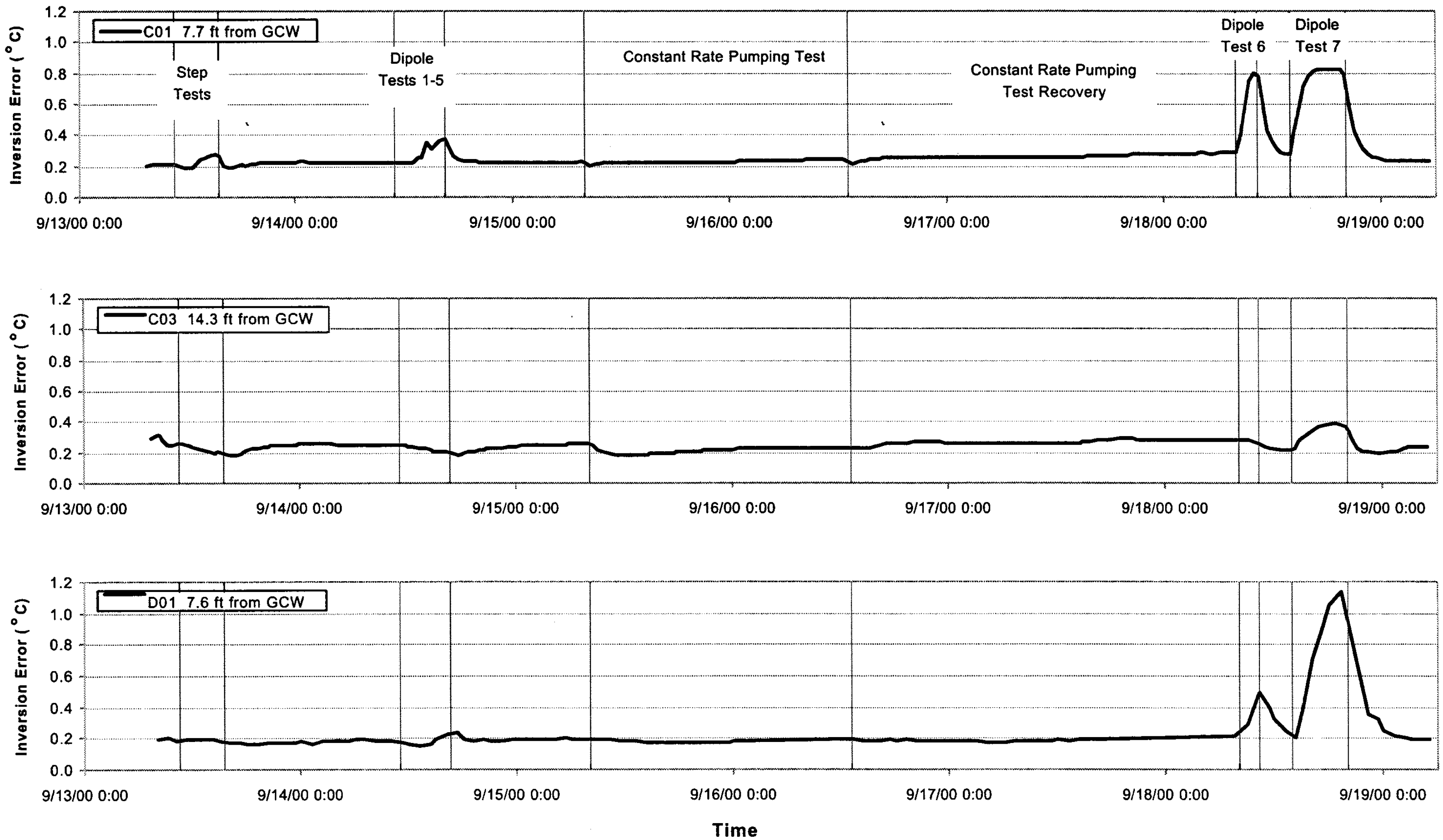


NOTES:
1) Aquifer testing period was from September 13 to 19, 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 47
Horizontal Groundwater Darcy Velocity Versus Time in Shallow Aquifer Zone Measured by Flow Sensors During Aquifer Testing Period (Data with Background Removed)

Tetra Tech EM Inc.

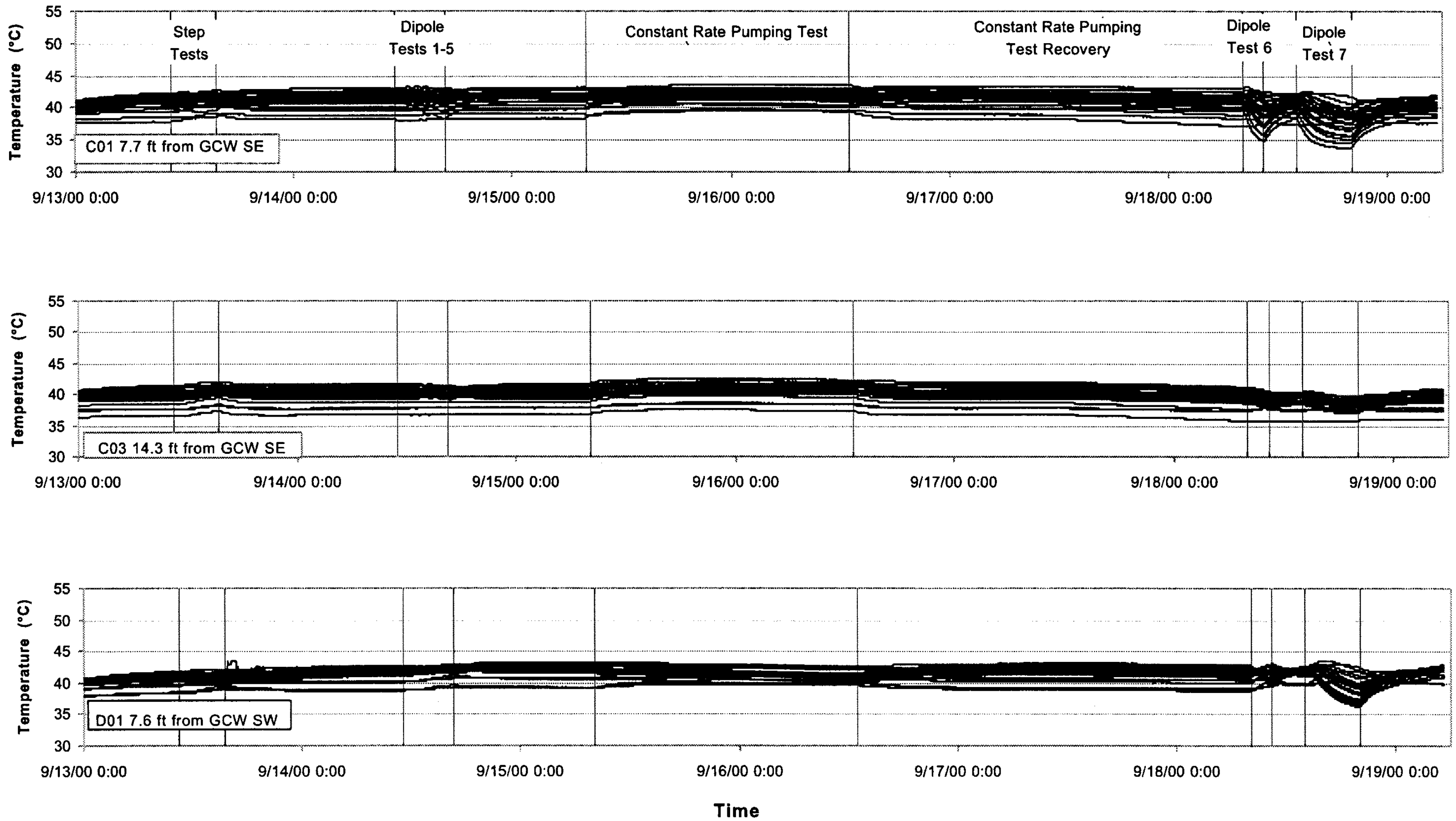


NOTES:
1) Aquifer testing period was from September 13 to 19, 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 48
Inversion Error Versus Time in Shallow Aquifer Zone Flow Sensors During Aquifer Testing Period

Tetra Tech EM Inc.

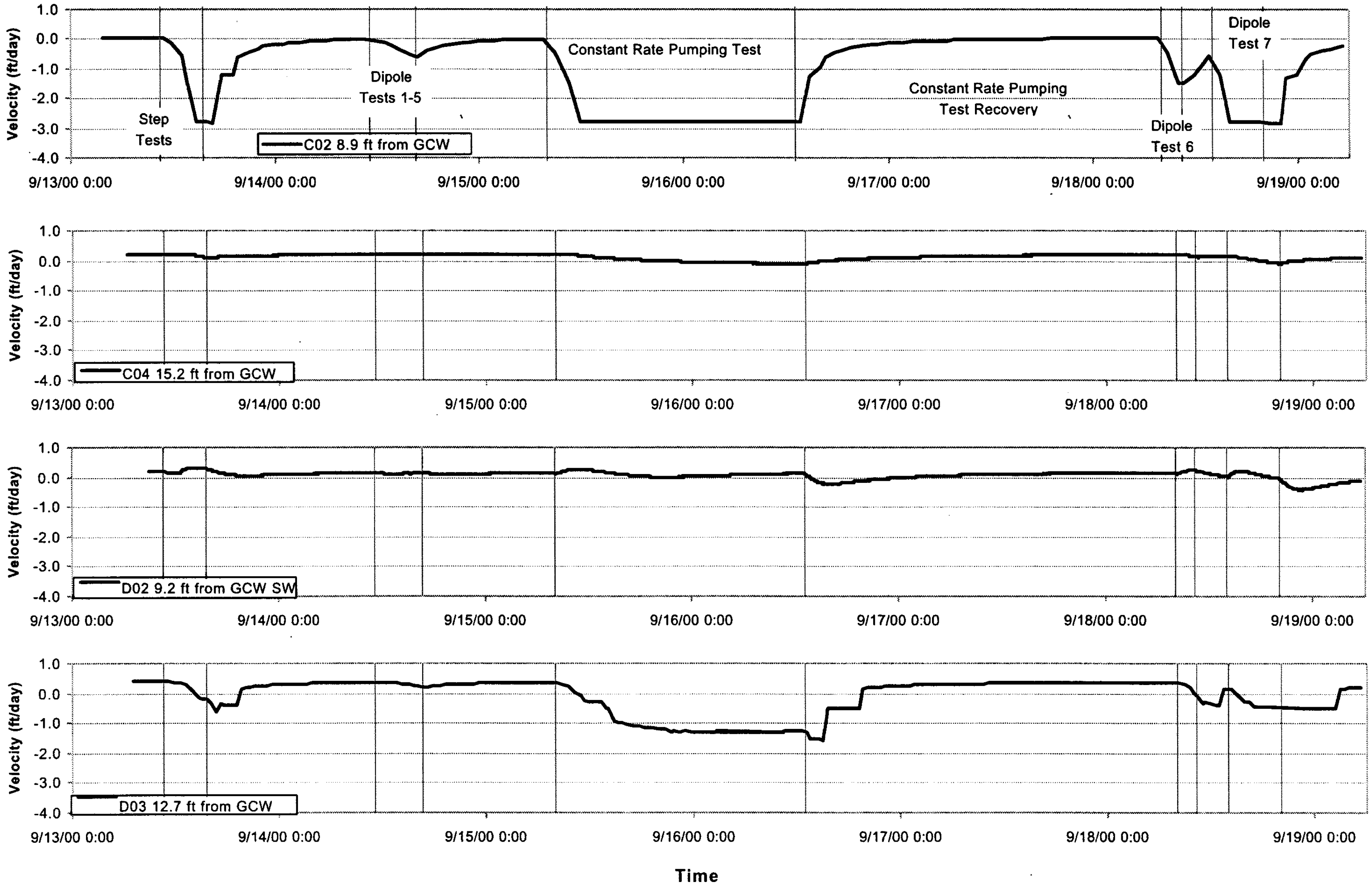


NOTES:
1) Aquifer testing period was from September 13 to 19, 2000.
2) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 49
Thermistor Temperature Versus Time in Shallow Aquifer Zone Flow Sensors During Aquifer Testing Period

Tetra Tech EM Inc.

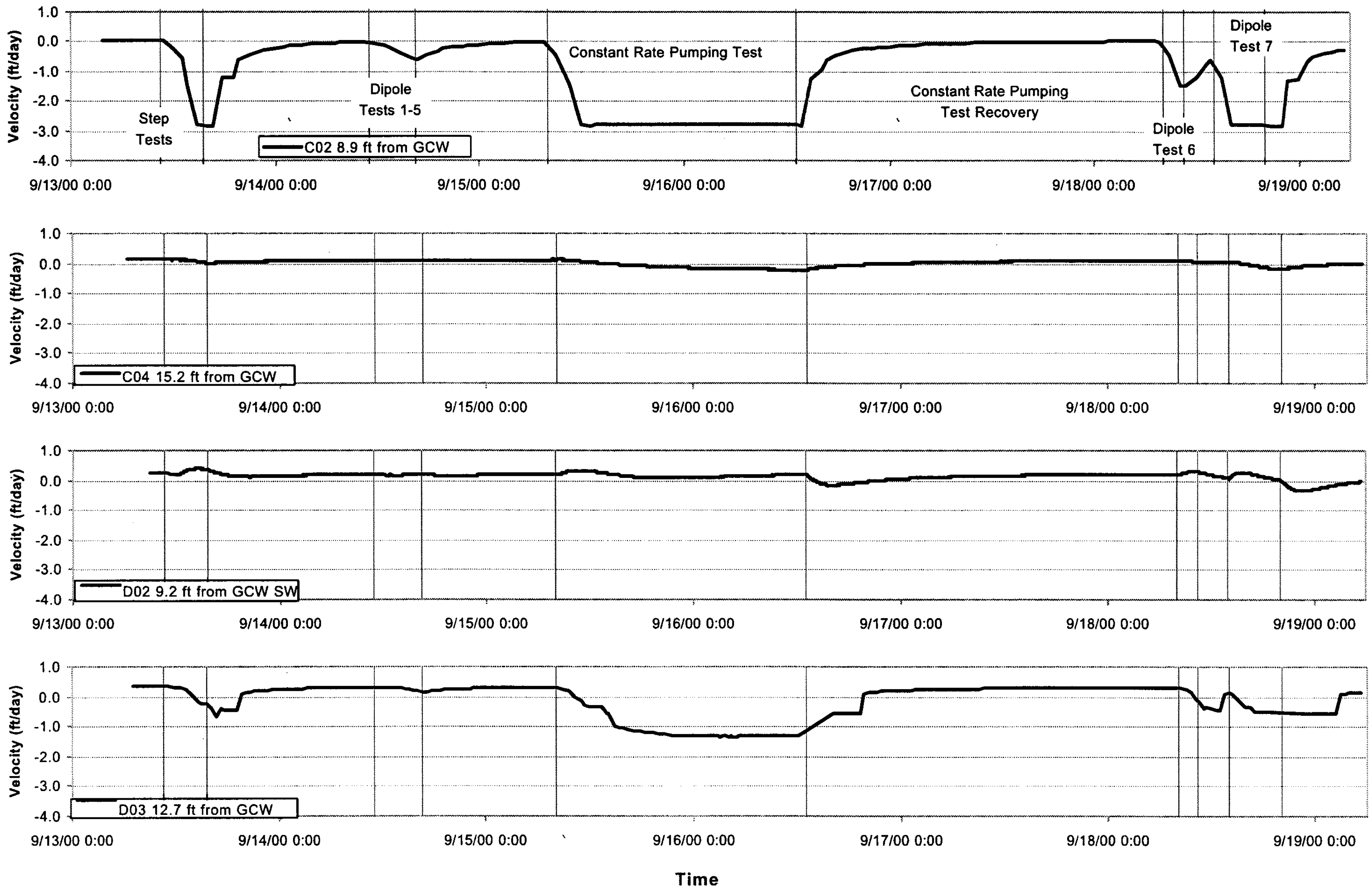


NOTES:
1) Aquifer testing period was from September 13 to 19, 2000.
2) Positive vertical velocity is indicative of upward hydraulic gradient.
3) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 50
Vertical Groundwater Darcy Velocity Versus Time in Deep Aquifer Zone Measured by Flow Sensors During Aquifer Testing Period (Actual Data)

Tetra Tech EM Inc.



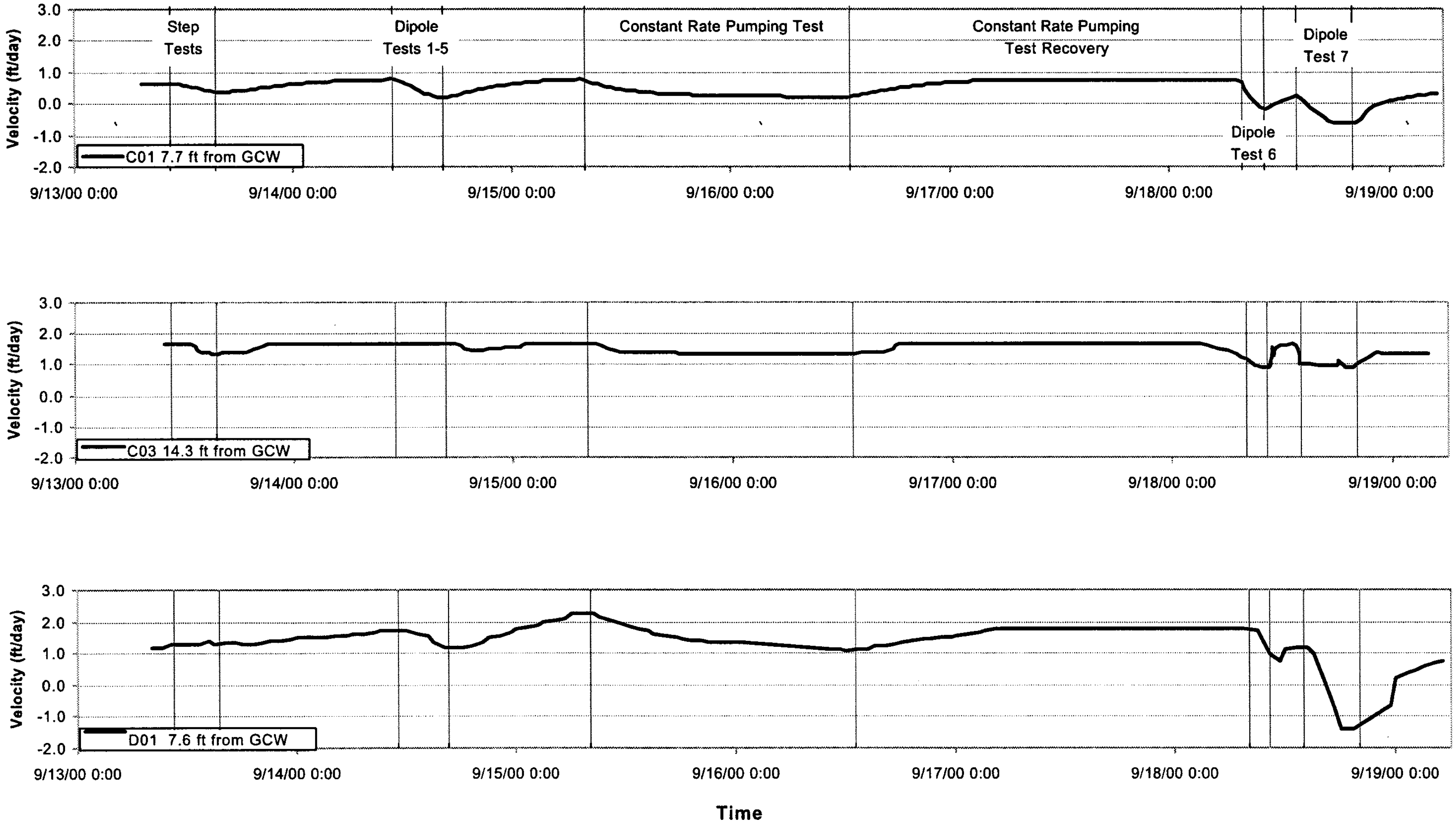
NOTES:

1) Aquifer testing period was from September 13 to 19, 2000.
2) Positive vertical velocity is indicative of upward hydraulic gradient.
3) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 51
Vertical Groundwater Darcy Velocity Versus Time in Deep Aquifer Zone Measured by Flow Sensors During Aquifer Testing Period (Data with Background Removed)

Tetra Tech EM Inc.



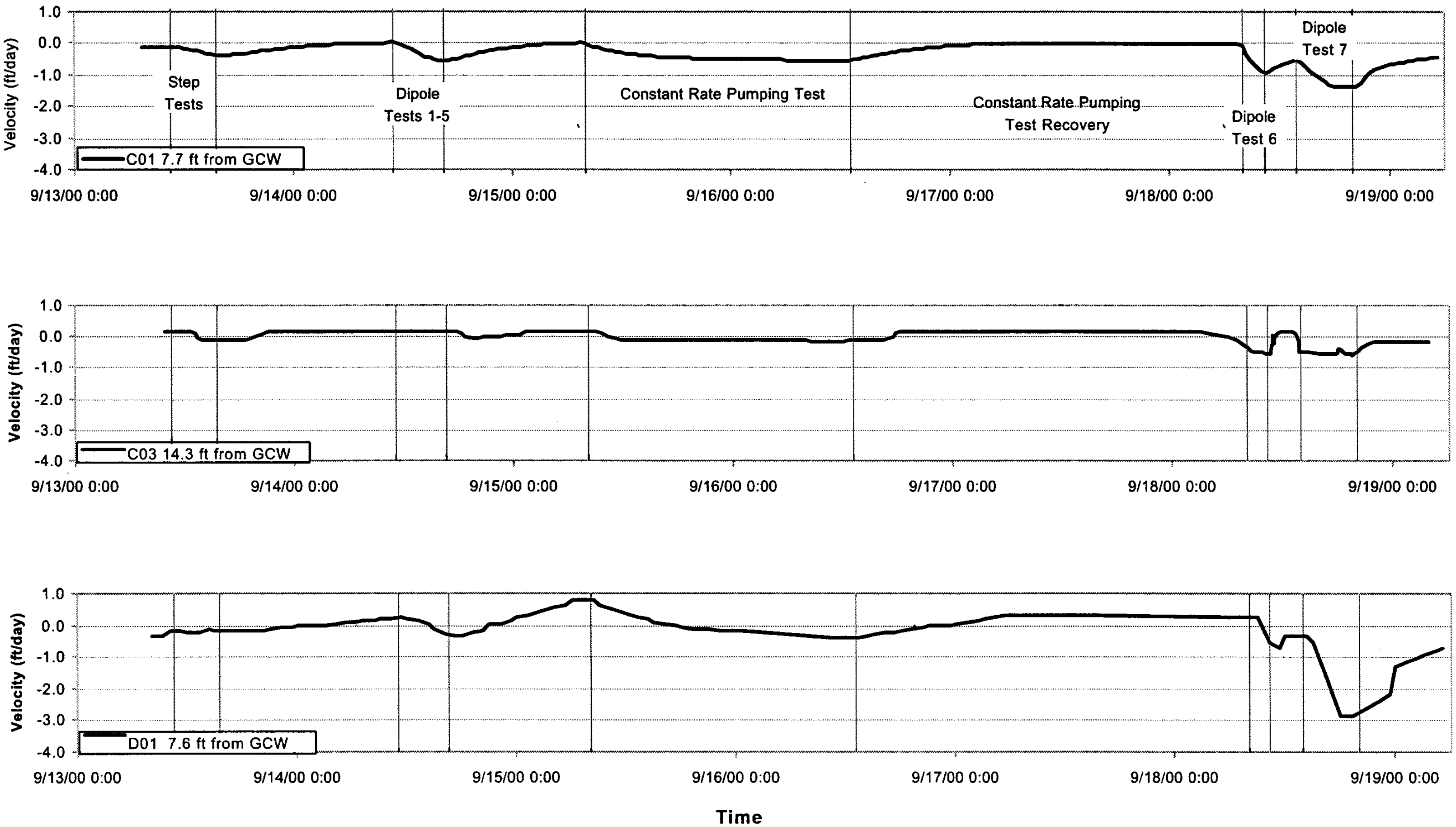
NOTES:

1) Aquifer testing period was from September 13 to 19, 2000.
2) Positive vertical velocity is indicative of upward hydraulic gradient.
3) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 52
Vertical Groundwater Darcy Velocity Versus Time in Shallow Aquifer Zone Measured by Flow Sensors During Aquifer Testing Period (Actual Data)

Tetra Tech EM Inc.

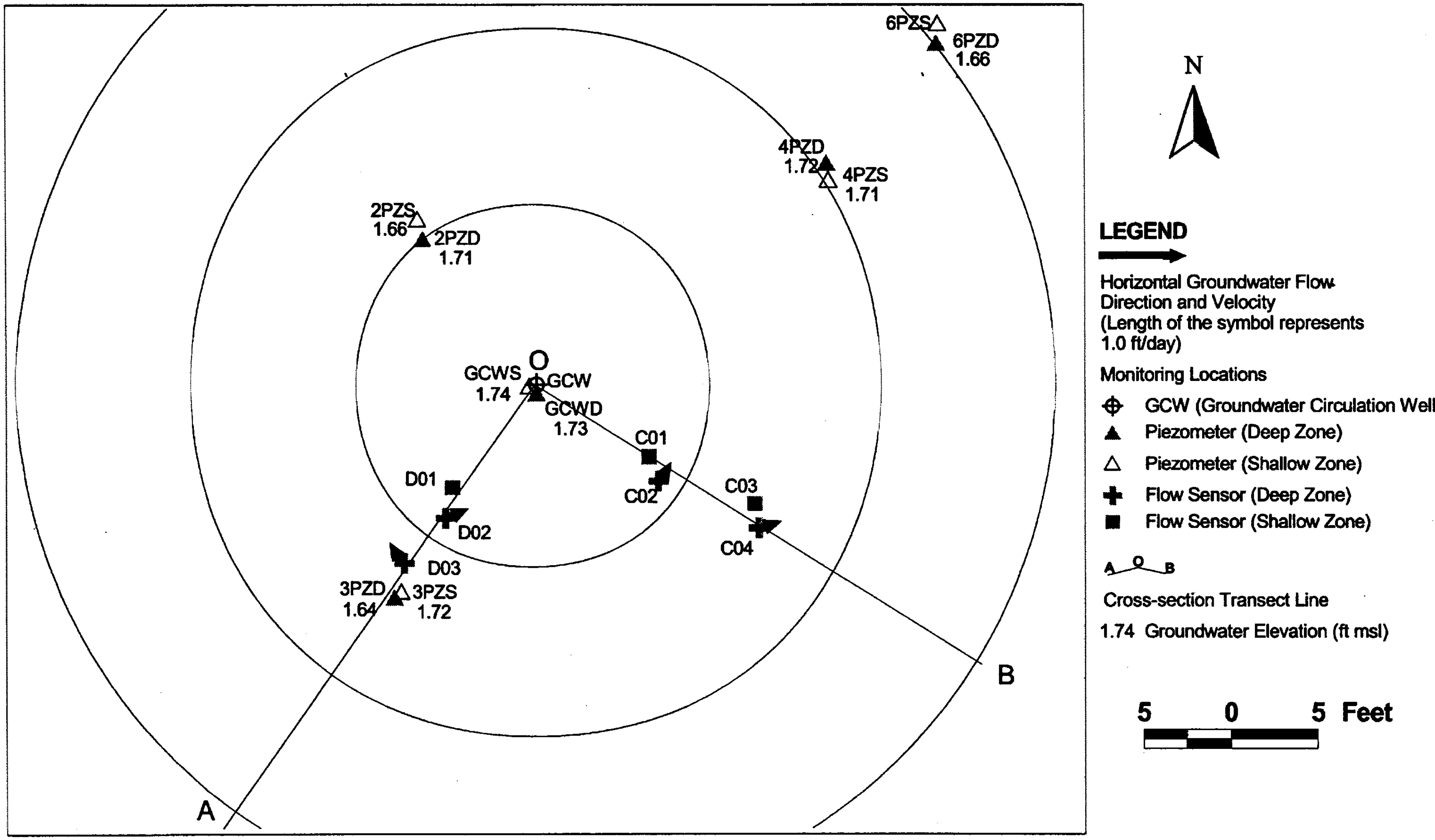


NOTES:
1) Aquifer testing period was from September 13 to 19, 2000.
2) Positive vertical velocity is indicative of upward hydraulic gradient.
3) Vertical lines indicate the beginning and end of aquifer testing events.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 53
Vertical Groundwater Darcy Velocity Versus Time in Shallow Aquifer Zone Measured by Flow Sensors During Aquifer Testing Period (Data with Background Removed)

Tetra Tech EM Inc.



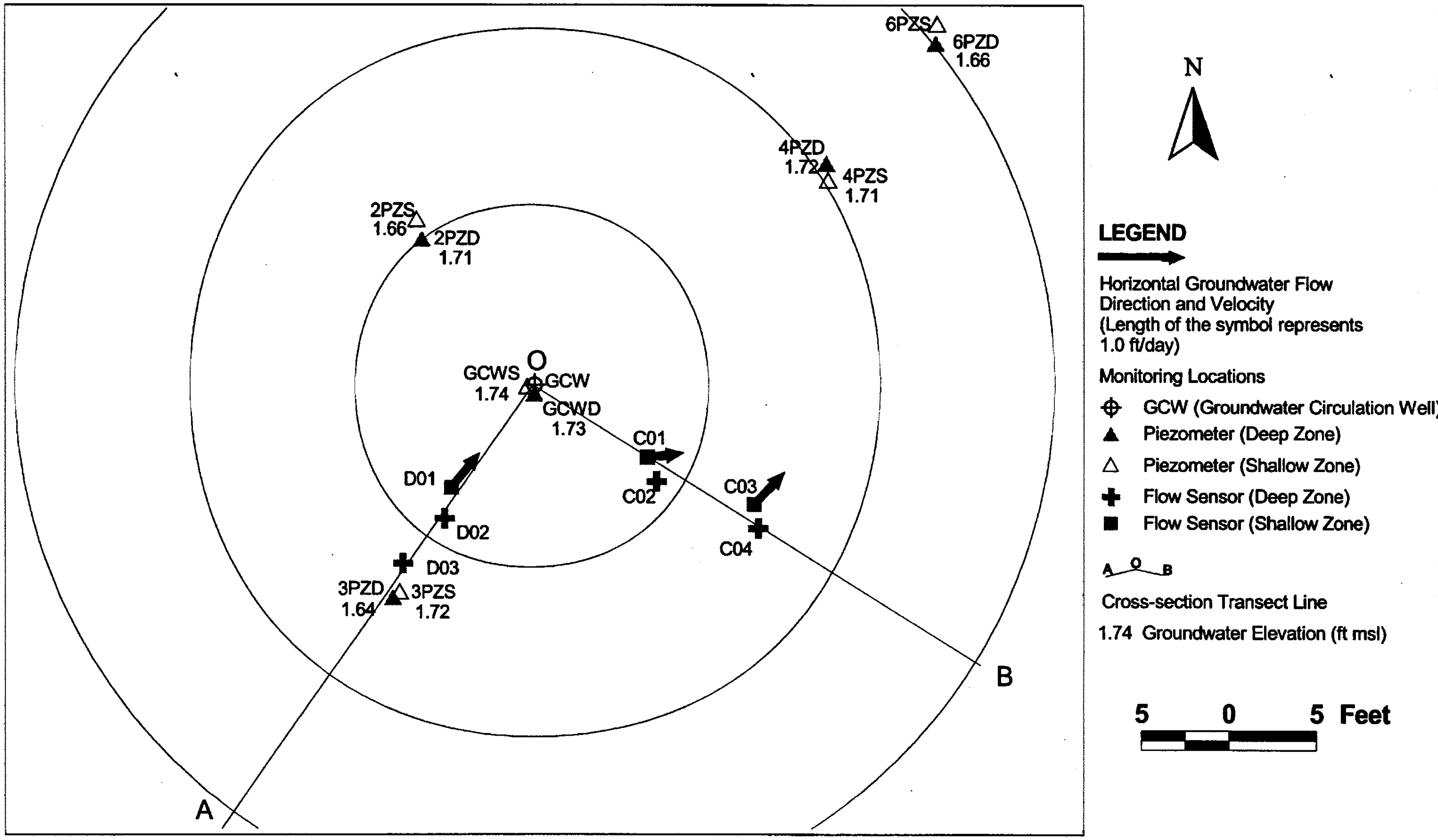
Resultant Data

NOTES:
1) Recovery period of the constant rate pumping test was from September 16 to 18, 2000 and lasted 43 hours.
2) Flow sensor data shown is from later stage of the recovery period of constant rate pumping test and considered to be representative of static conditions.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 54
Horizontal Groundwater Darcy Velocity in Deep Aquifer Zone Measured by Flow Sensors Under Natural Flow Conditions (09/18/00)

Tetra Tech EM Inc.



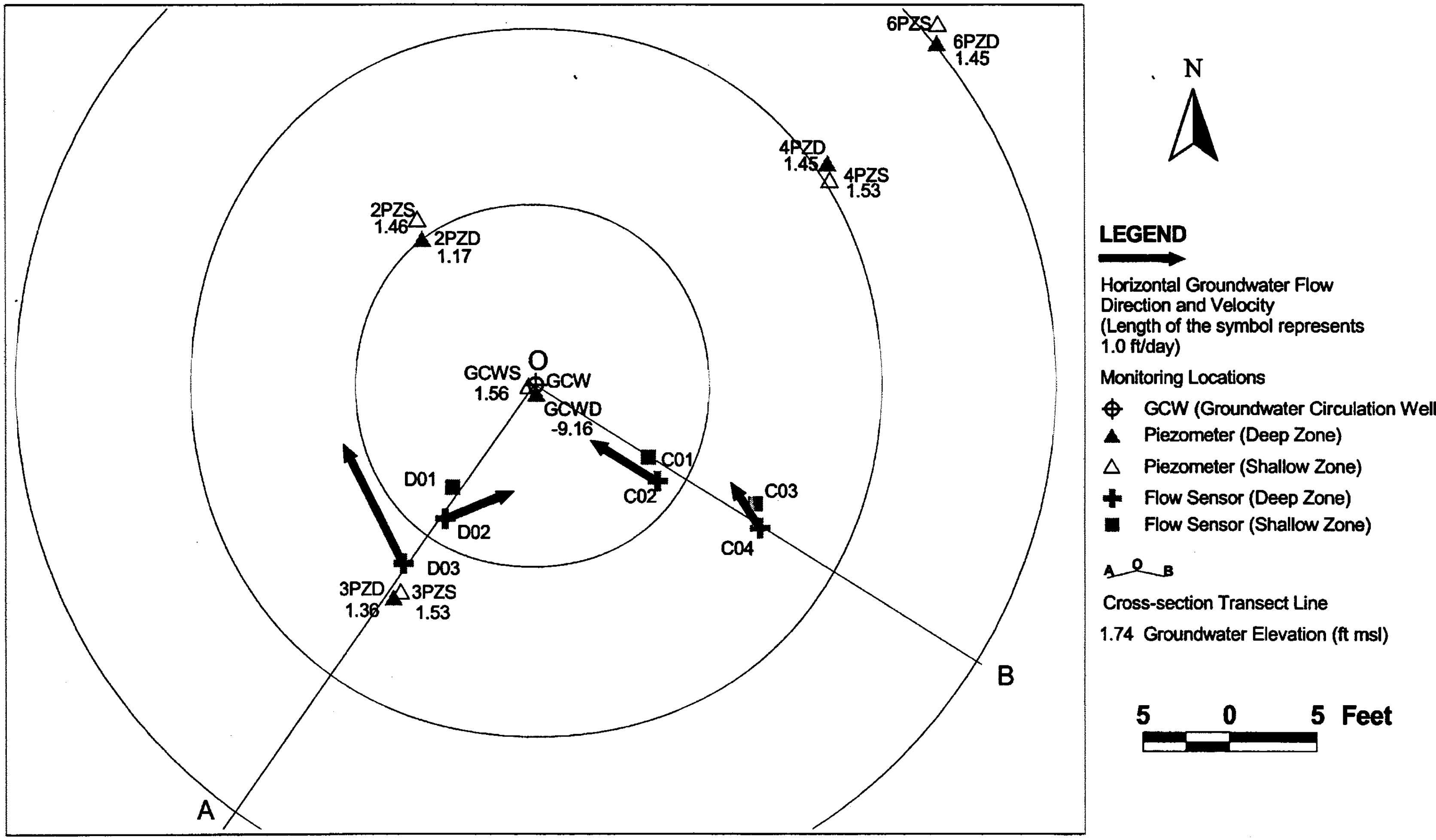
Resultant Data

NOTES:
1) Recovery period of the constant rate pumping test was from September 16 to 18, 2000 and lasted 43 hours.
2) Flow sensor data shown is from later stage of the recovery period of constant rate pumping test and considered to be representative of static conditions.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 55
Horizontal Groundwater Darcy Velocity in Shallow Aquifer Zone Measured by Flow Sensors Under Natural Flow Conditions (09/18/00)

Tetra Tech EM Inc.



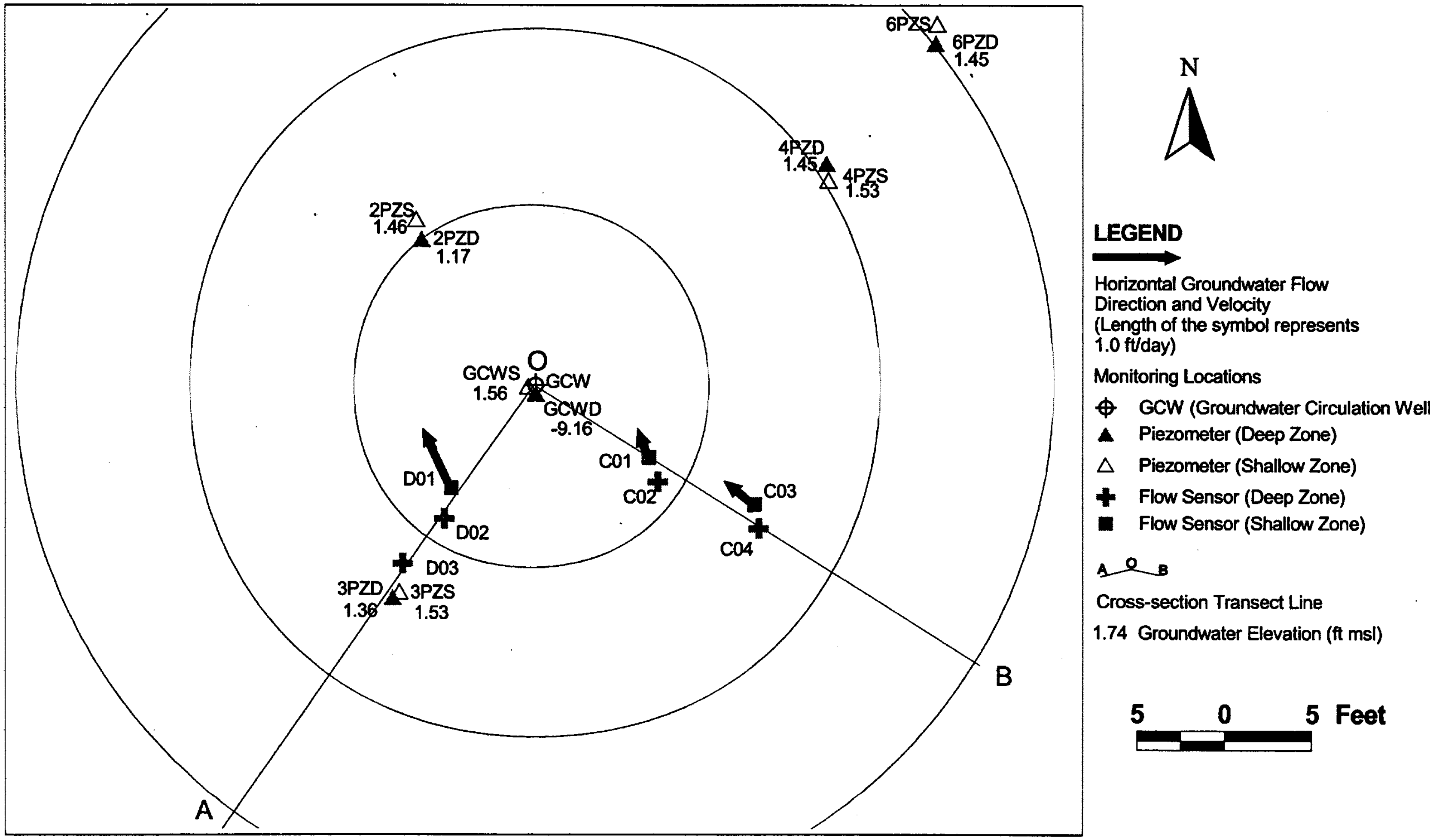
Resultant Data

NOTES:
1) Constant rate pumping test was conducted for 29 hours on September 15 and 16, 2000, using pumping rate of 10 gpm.
2) Flow sensor data shown is from later stage of the constant rate pumping test and considered to be representative of steady-state conditions.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 56
Horizontal Groundwater Darcy Velocity in Deep Aquifer Zone Measured by Flow Sensors Under Pumping Conditions (09/16/00)

Tetra Tech EM Inc.



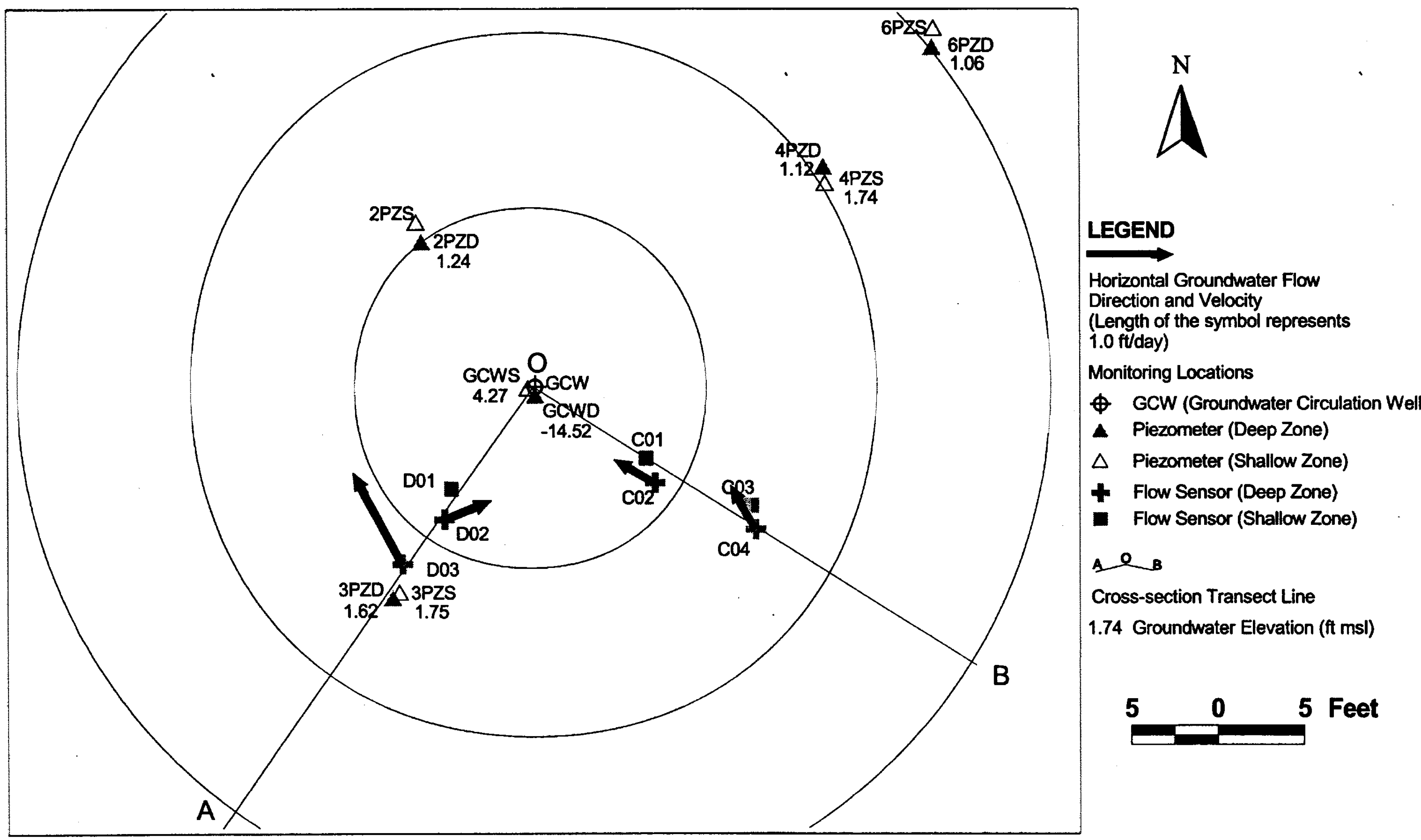
Resultant Data

NOTES:
1) Constant rate pumping test was conducted for 29 hours on September 15 and 16, 2000, using pumping rate of 10 gpm.
2) Flow sensor data shown is from later stage of the constant rate pumping test and considered to be representative of steady-state conditions.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 57
Horizontal Groundwater Darcy Velocity in Shallow Aquifer Zone Measured by Flow Sensors Under Pumping Conditions (09/16/00)

Tetra Tech EM Inc.



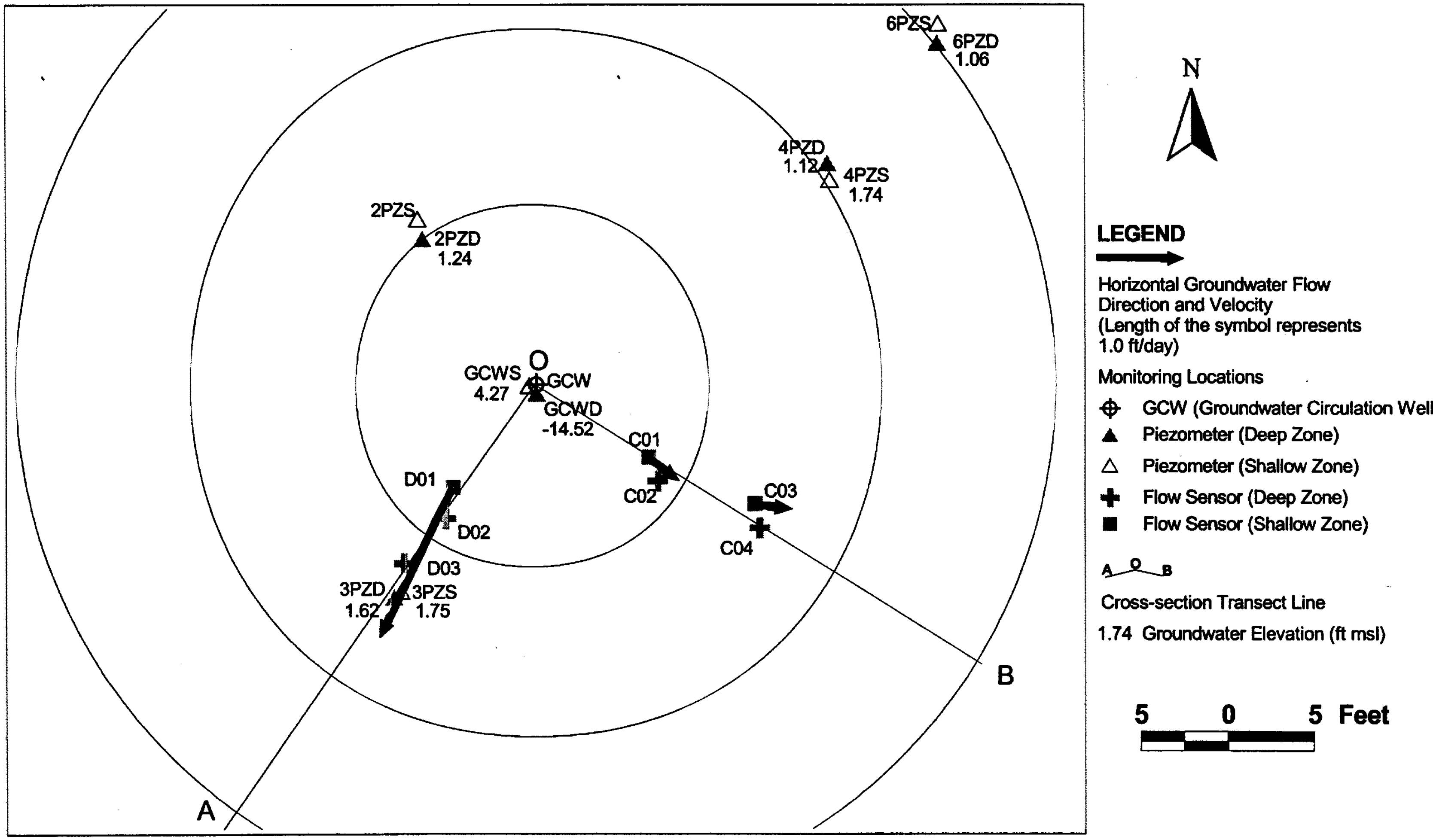
Resultant Data

NOTES:
1) Dipole testing consisted of pumping groundwater from the lower screened interval of the GCW and injecting it into the upper screened interval of the GCW.
2) Dipole test 6 was conducted from 8:00 am to 10:22 am on 9/18/00, using a pumping and injection rate of 12.5 gpm.
3) No groundwater elevation data was collected from 2PZS because the pressure transducer was not functioning.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 58
Horizontal Groundwater Darcy Velocity in Deep Aquifer Zone Measured by Flow Sensors During Dipole Test 6 (09/18/00)

Tetra Tech EM Inc.



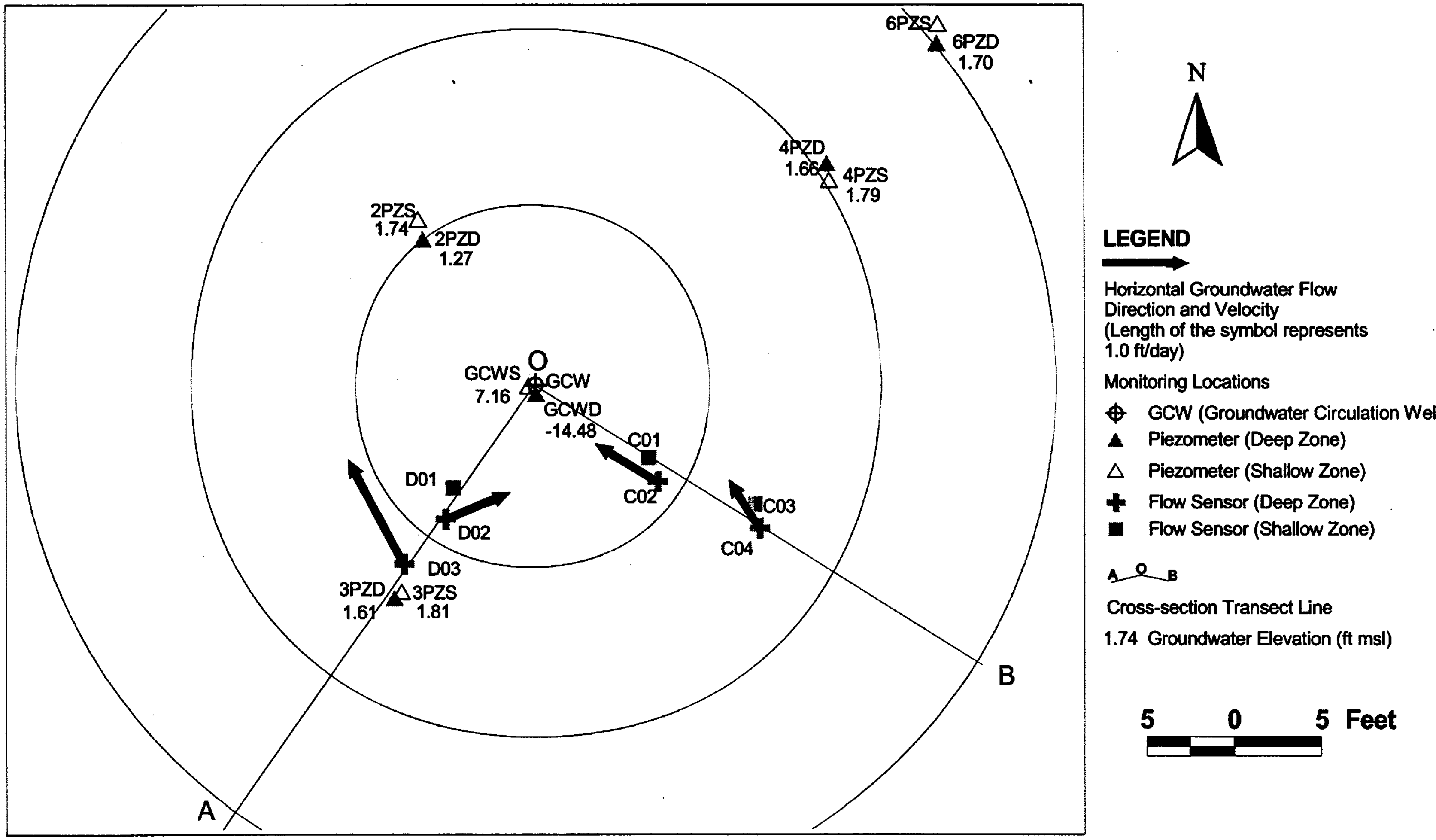
Resultant Data

NOTES:
1) Dipole testing consisted of pumping groundwater from the lower screened interval of the GCW and injecting it into the upper screened interval of the GCW.
2) Dipole test 6 was conducted from 8:00 am to 10:22 am on 9/18/00, using a pumping and injection rate of 12.5 gpm.
3) No groundwater elevation data was collected from 2PZS because the pressure transducer was not functioning.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 59
Horizontal Groundwater Darcy Velocity in Shallow Aquifer Zone Measured by Flow Sensors During Dipole Test 6 (09/18/00)

Tetra Tech EM Inc.



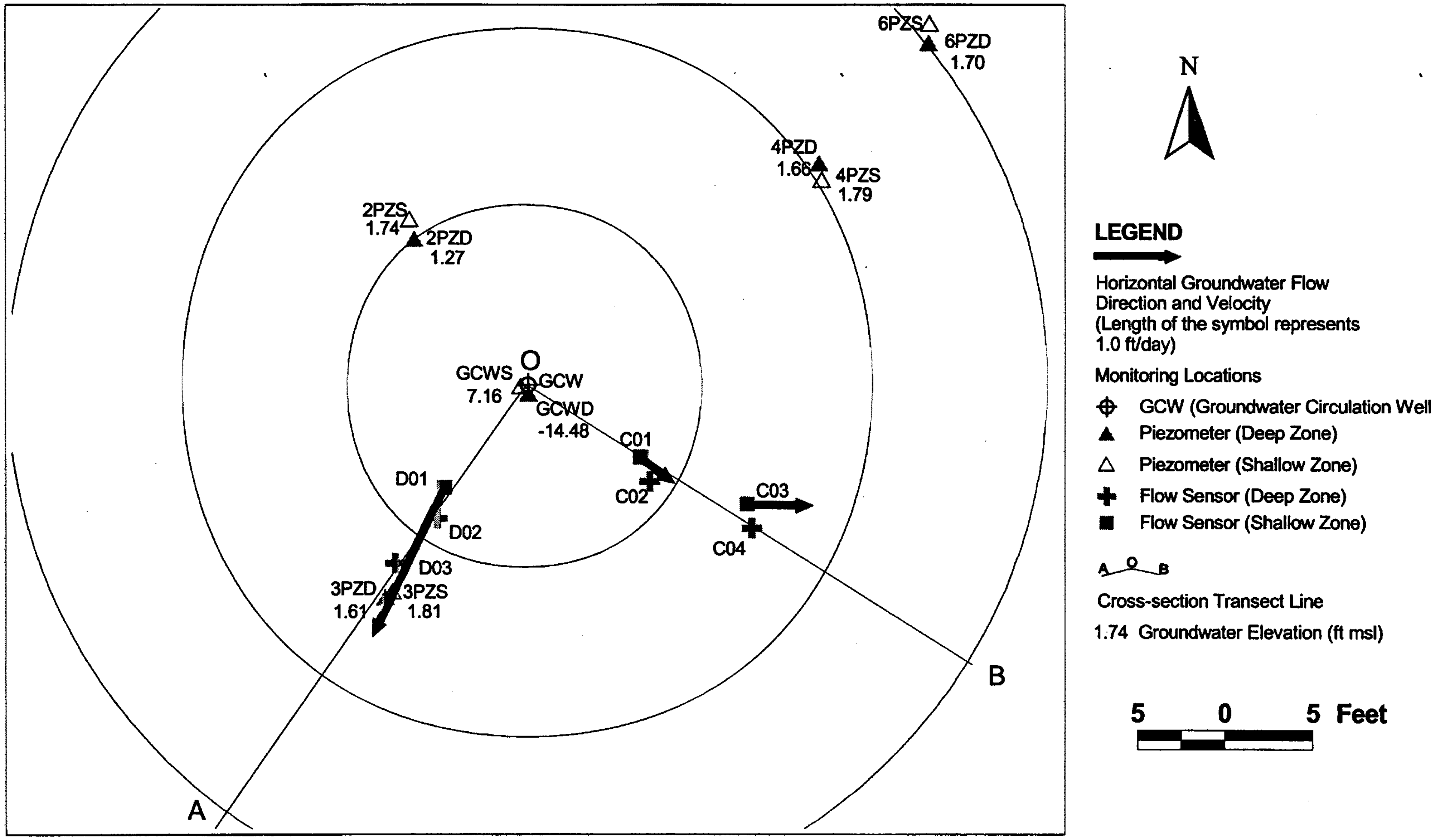
Resultant Data

NOTES:
1) Dipole testing consisted of pumping groundwater from the lower screened interval of the GCW and injecting it into the upper screened interval of the GCW.
2) Dipole test 7 was conducted from 2:00 pm to 8:00 pm on 9/18/00, using a pumping and injection rate of 12.5 gpm.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 60
Horizontal Groundwater Darcy Velocity in Deep Aquifer Zone Measured by Flow Sensors During Dipole Test 7 (09/18/00)

Tetra Tech EM Inc.



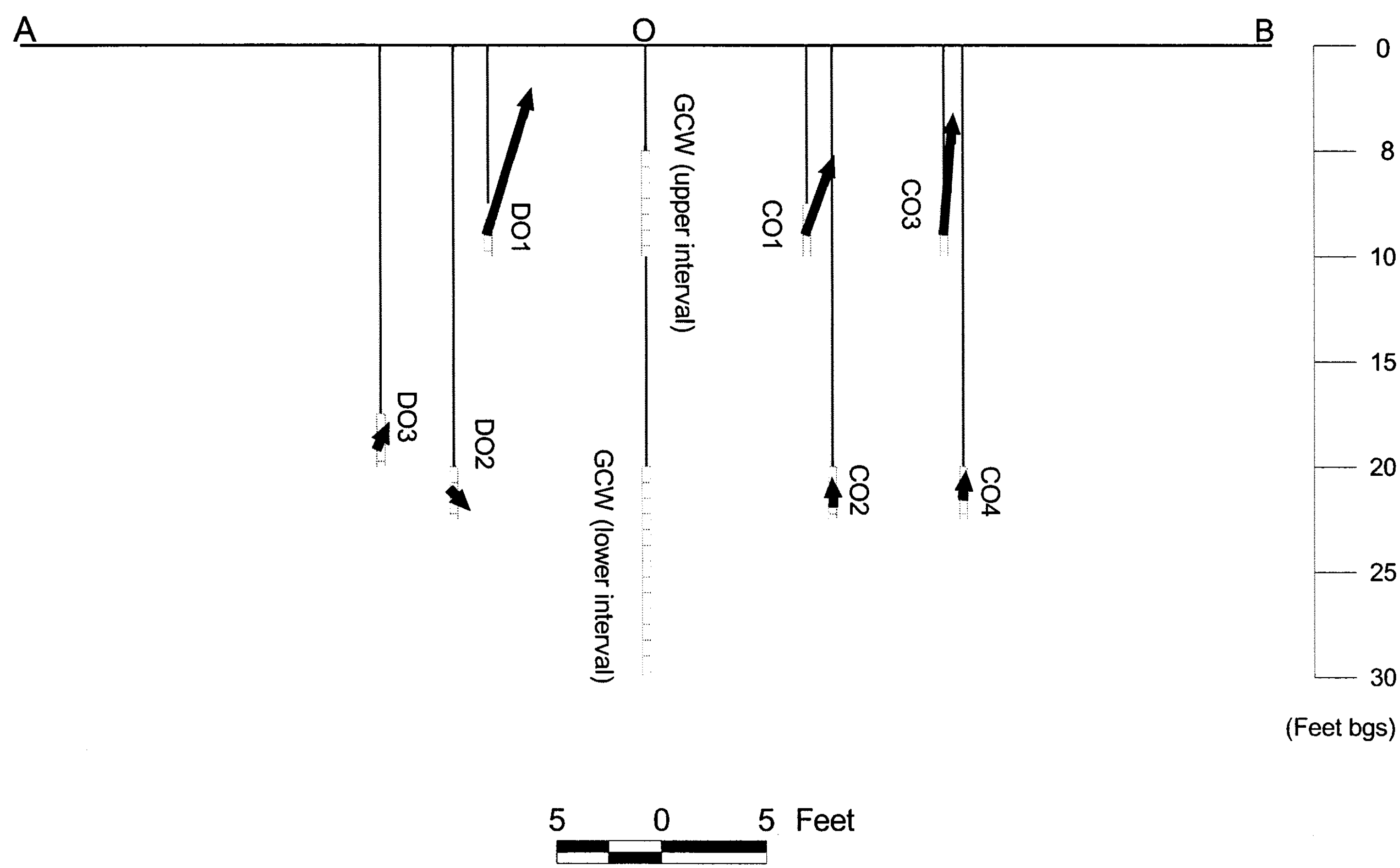
Resultant Data

NOTES:
1) Dipole testing consisted of pumping groundwater from the lower screened interval of the GCW and injecting it into the upper screened interval of the GCW.
2) Dipole test 7 was conducted from 2:00 pm to 8:00 pm on 9/18/00, using a pumping and injection rate of 12.5 gpm.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 61
Horizontal Groundwater Darcy Velocity in Shallow Aquifer Zone Measured by Flow Sensors During Dipole Test 7 (09/18/00)

Tetra Tech EM Inc.



LEGEND

Groundwater Flow Direction and Velocity
(Length of the symbol represents 1.0 ft/day)

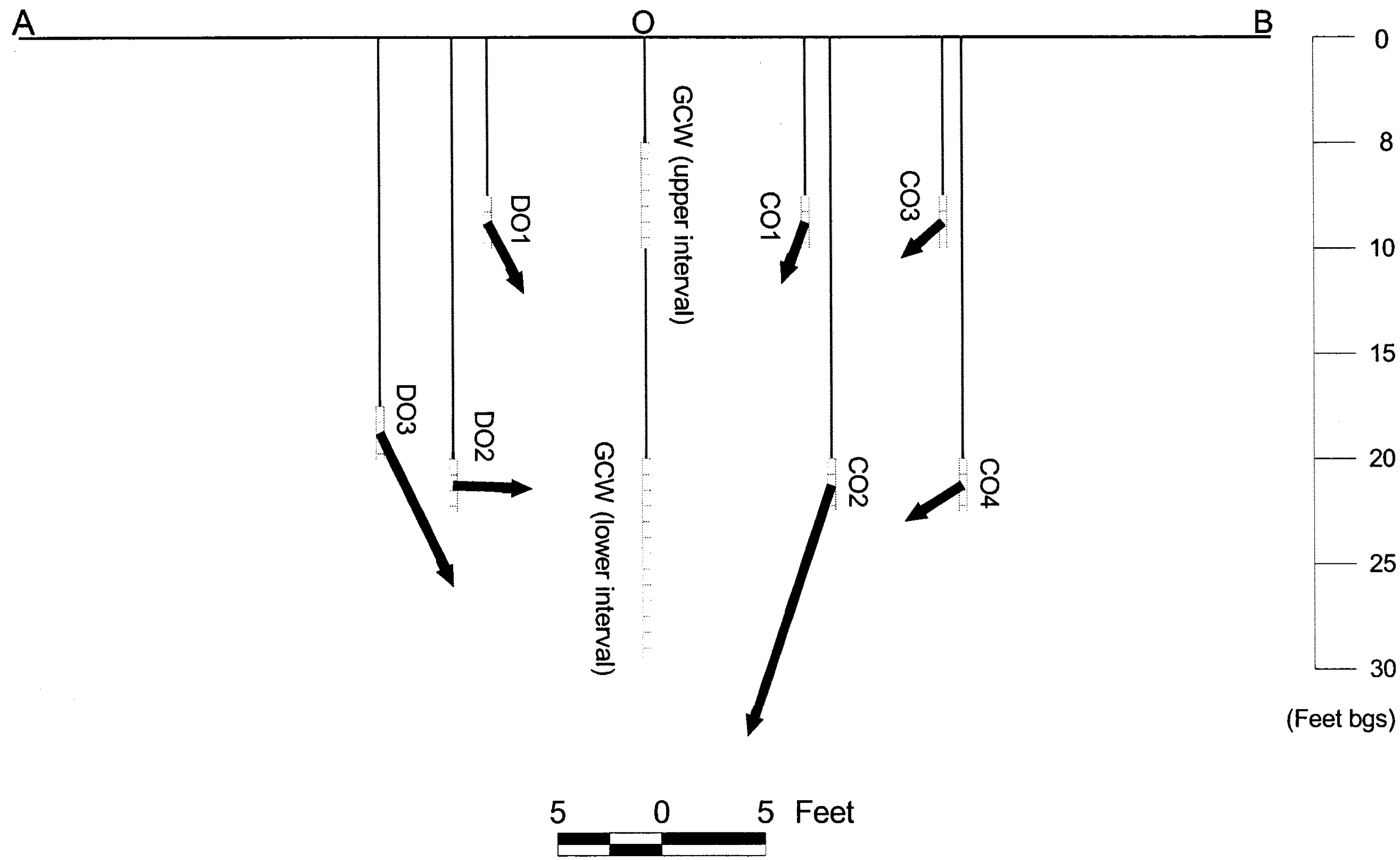
Flow Sensor Interval and GCW Screened Interval

NOTE:
1) Cross-section transect line location is shown on Figure 3.
2) Recovery period of the constant rate pumping test was from September 16 to 18, 2000 and lasted 43 hours.
3) Flow sensor data shown is from later stage of the recovery period of constant rate pumping test and considered to be representative of static conditions.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 62
Resultant Groundwater Flow Velocity Projected onto Cross-Section AOB Under Natural Flow Conditions (09/18/00)

Tetra Tech EM Inc.



LEGEND

Groundwater Flow Direction and Velocity
(Length of the symbol represents 1.0 ft/day)

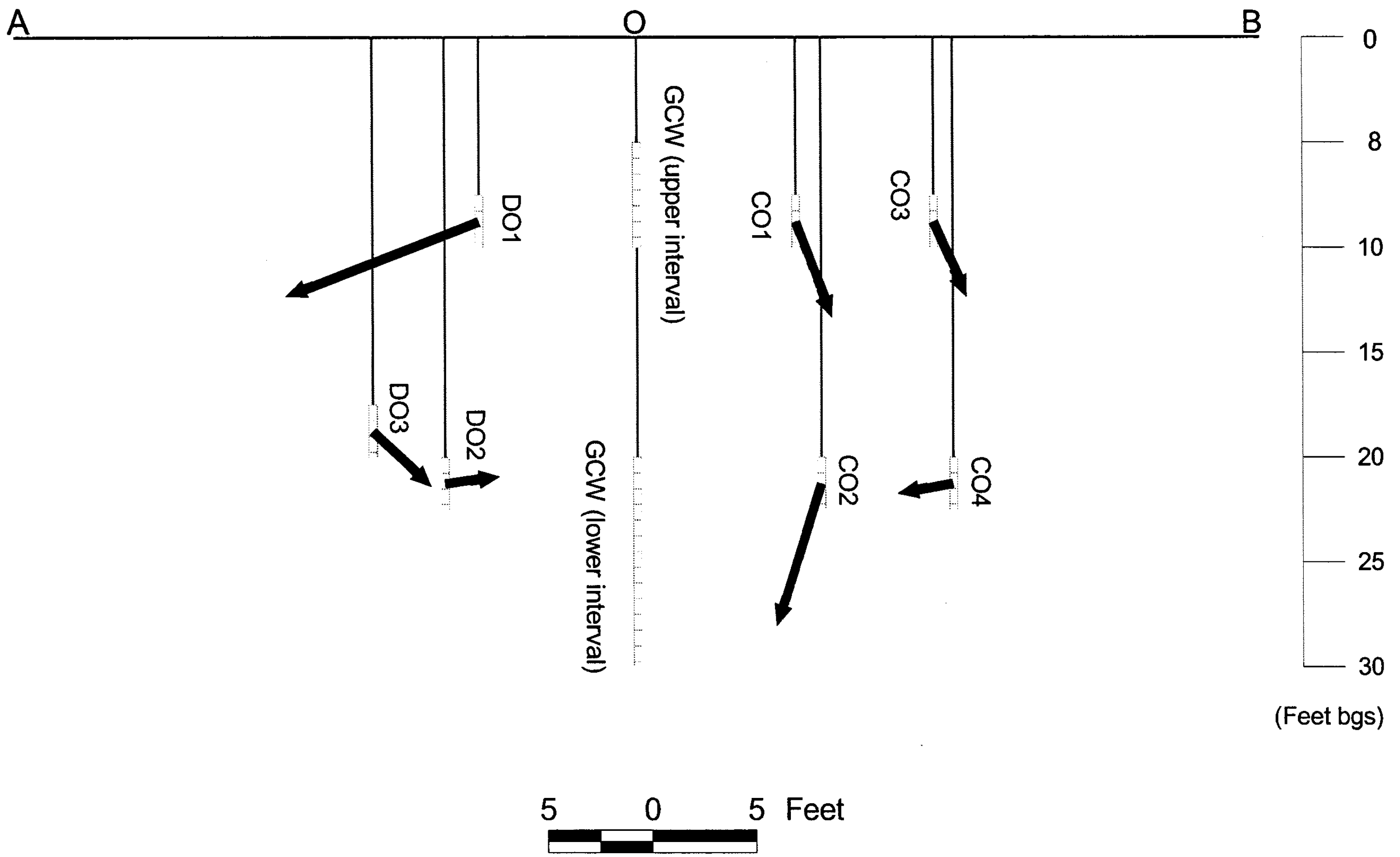
Flow Sensor Interval and GCW Screened Interval

NOTE:
1) Cross-section transect line location is shown on Figure 3.
2) Constant rate pumping test was conducted for 29 hours on September 15 and 16, 2000 using a pumping rate of 10 gpm.
3) Flow sensor data shown is from later stage of the recovery period of constant rate pumping test and considered to be representative of static conditions.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 63
Resultant Groundwater Flow Velocity Projected onto Cross-Section AOB Under Pumping Conditions (09/16/00)

Tetra Tech EM Inc.



LEGEND

Groundwater Flow Direction and Velocity
(Length of the symbol represents 1.0 ft/day)

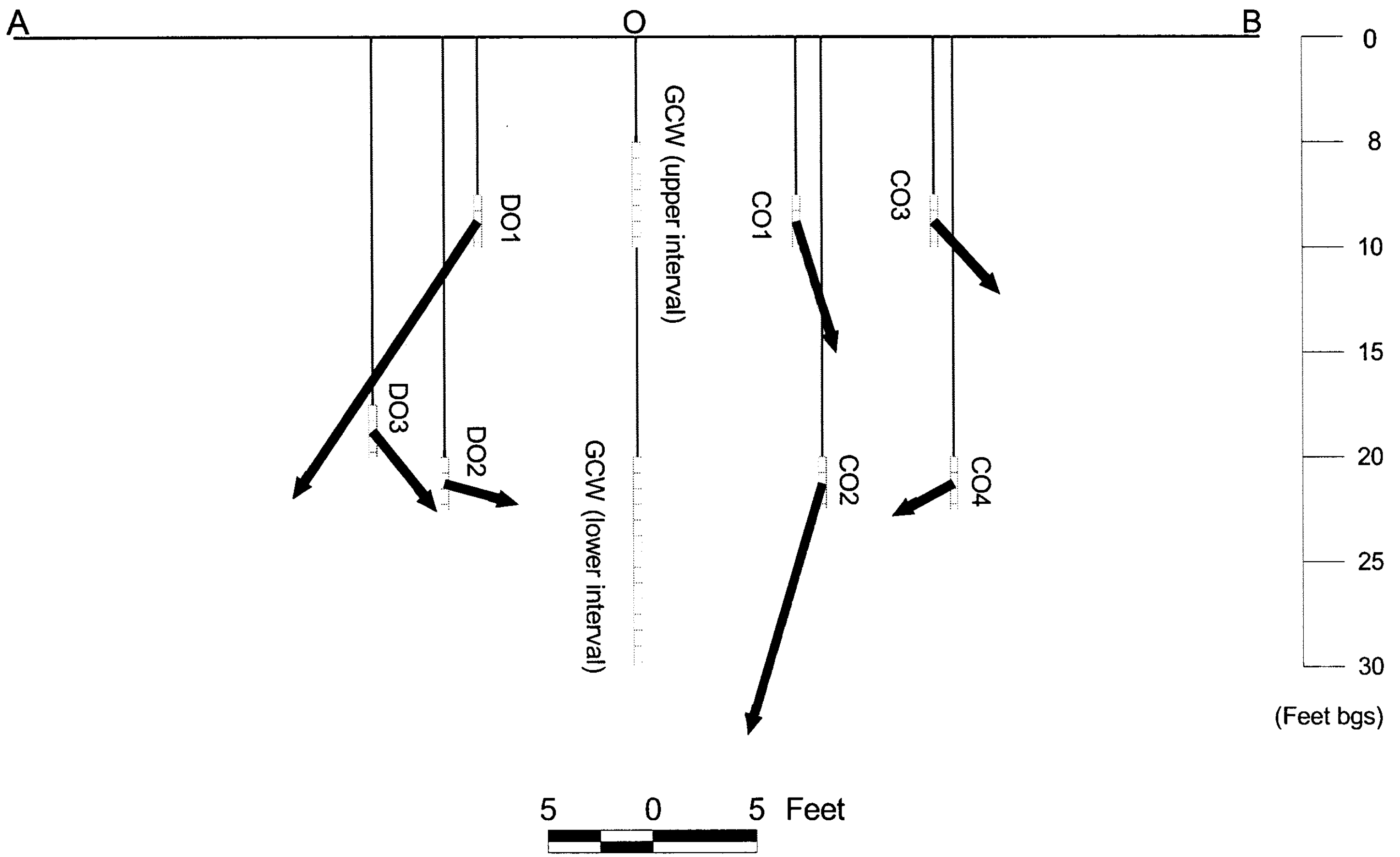
Flow Sensor Interval and GCW Screened Interval

NOTES:
1) Cross-section transect line location is shown on Figure 3.
2) Data evaluated is from Dipole Test 6 conducted from 8:00 am to 10:22 am on 9/18/00, using a pumping and injection rate of 12.5 gpm.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 64
Resultant Groundwater Flow Velocity Projected onto Cross-Section AOB During Dipole 6 (09/18/00)

Tetra Tech EM Inc.



LEGEND

Groundwater Flow Direction and Velocity
(Length of the symbol represents 1.0 ft/day)

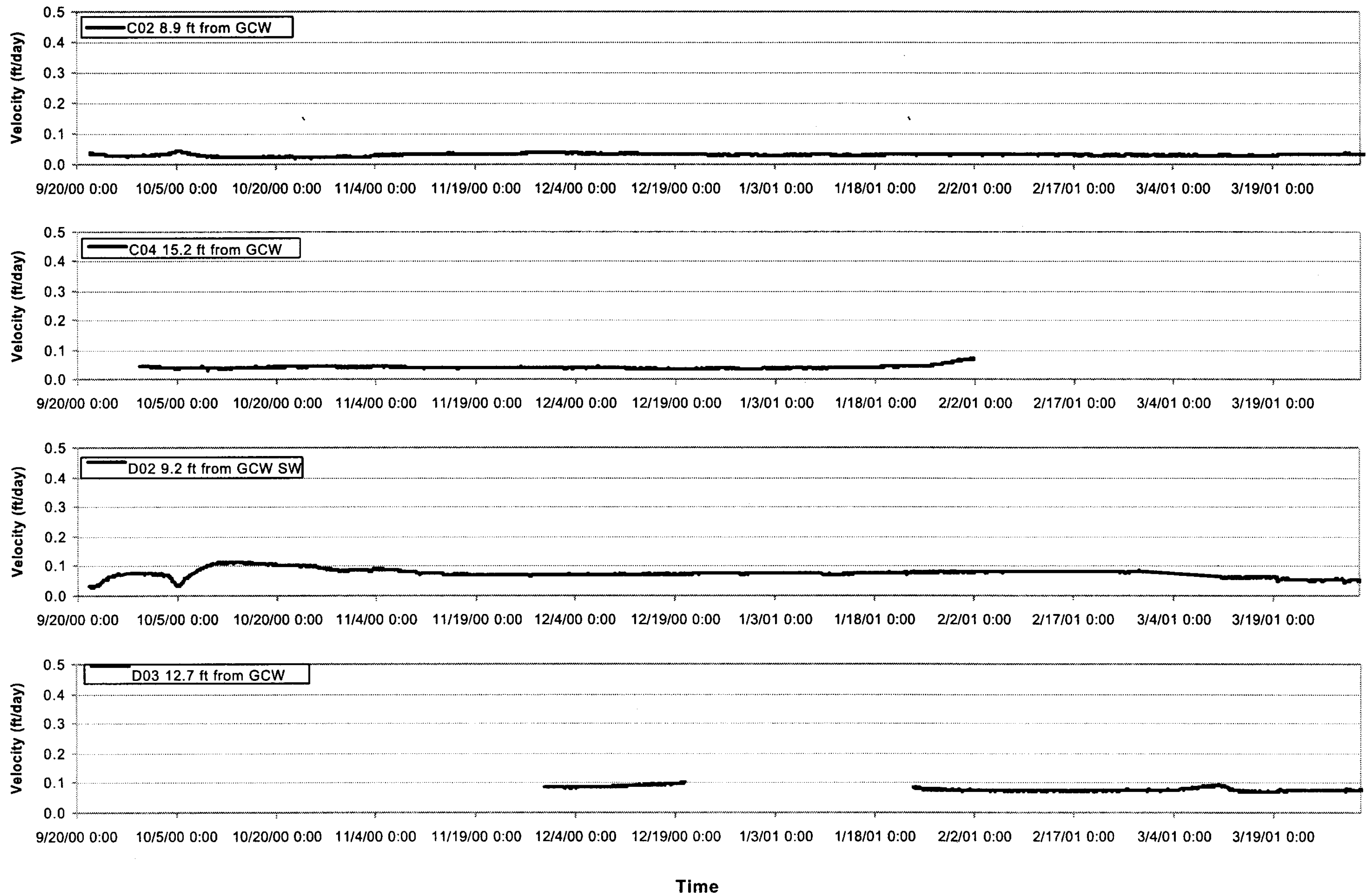
Flow Sensor Interval and GCW Screened Interval

NOTES:
1) Cross-section transect line location is shown on Figure 3.
2) Data evaluated is from Dipole Test 7 conducted from 2:00 pm to 8:00 pm on 9/18/00, using a pumping and injection rate of 12.5 gpm.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 65
Resultant Groundwater Flow Velocity Projected onto Cross-Section AOB During Dipole 7 (09/18/00)

Tetra Tech EM Inc.



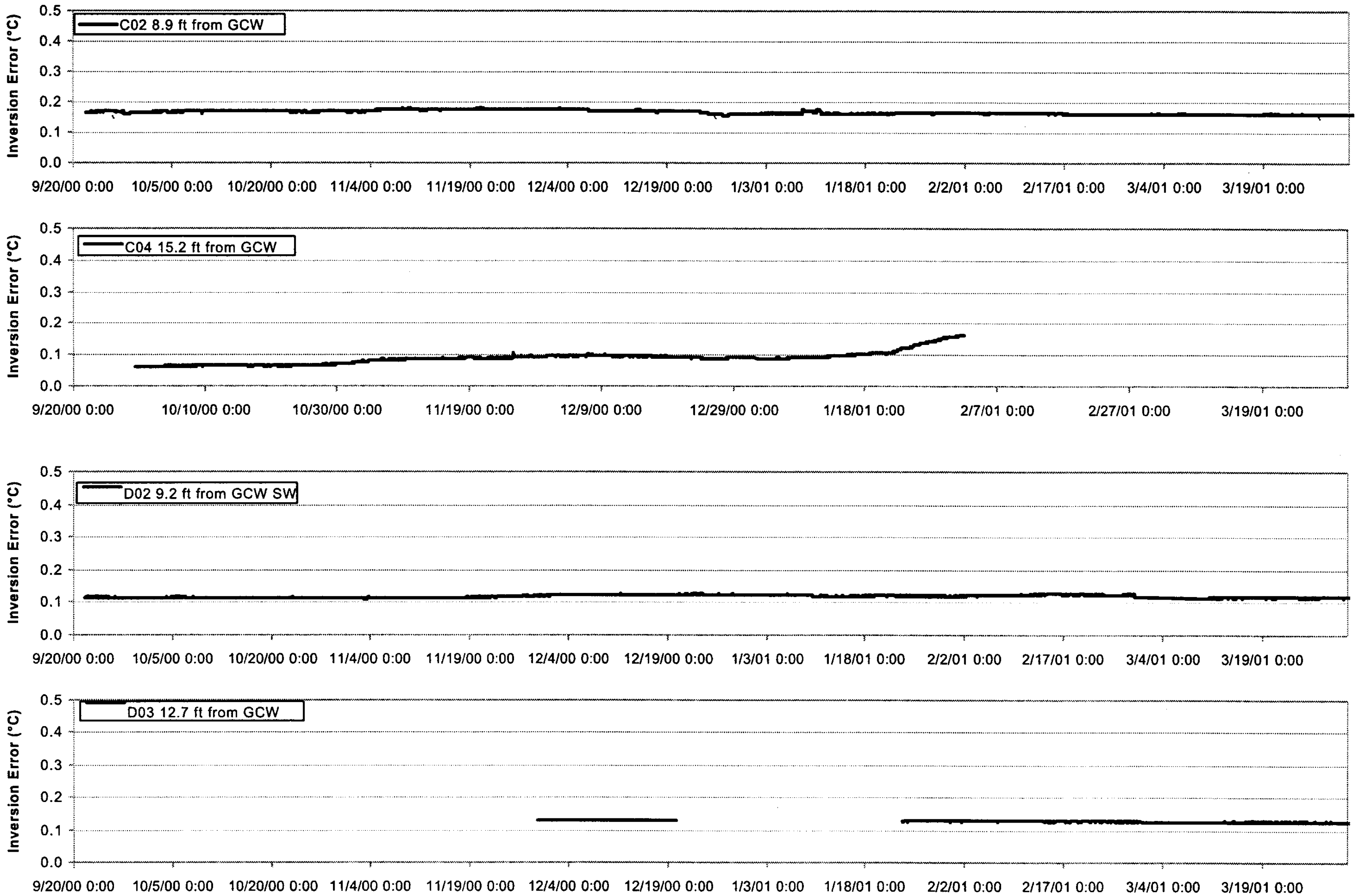
NOTES:

1) Data shown is from the post-test period from September 20, 2000 to April 1, 2001
2) Data at flow sensor C04 after February 2, 2001 were deleted. For unknown reasons, the original data contains a gradually temperature shift.
3) Data at flow sensor D03 from September 20 to November 30, 2000 and from December 20, 2000 to January 24, 2001 were deleted. The original data were affected by electrical noise.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 66
Horizontal Groundwater Darcy Velocity Versus Time in Deep Aquifer Zone Measured by Flow Sensors 9/20/00-4/1/01 (Actual Data)

Tetra Tech EM Inc.

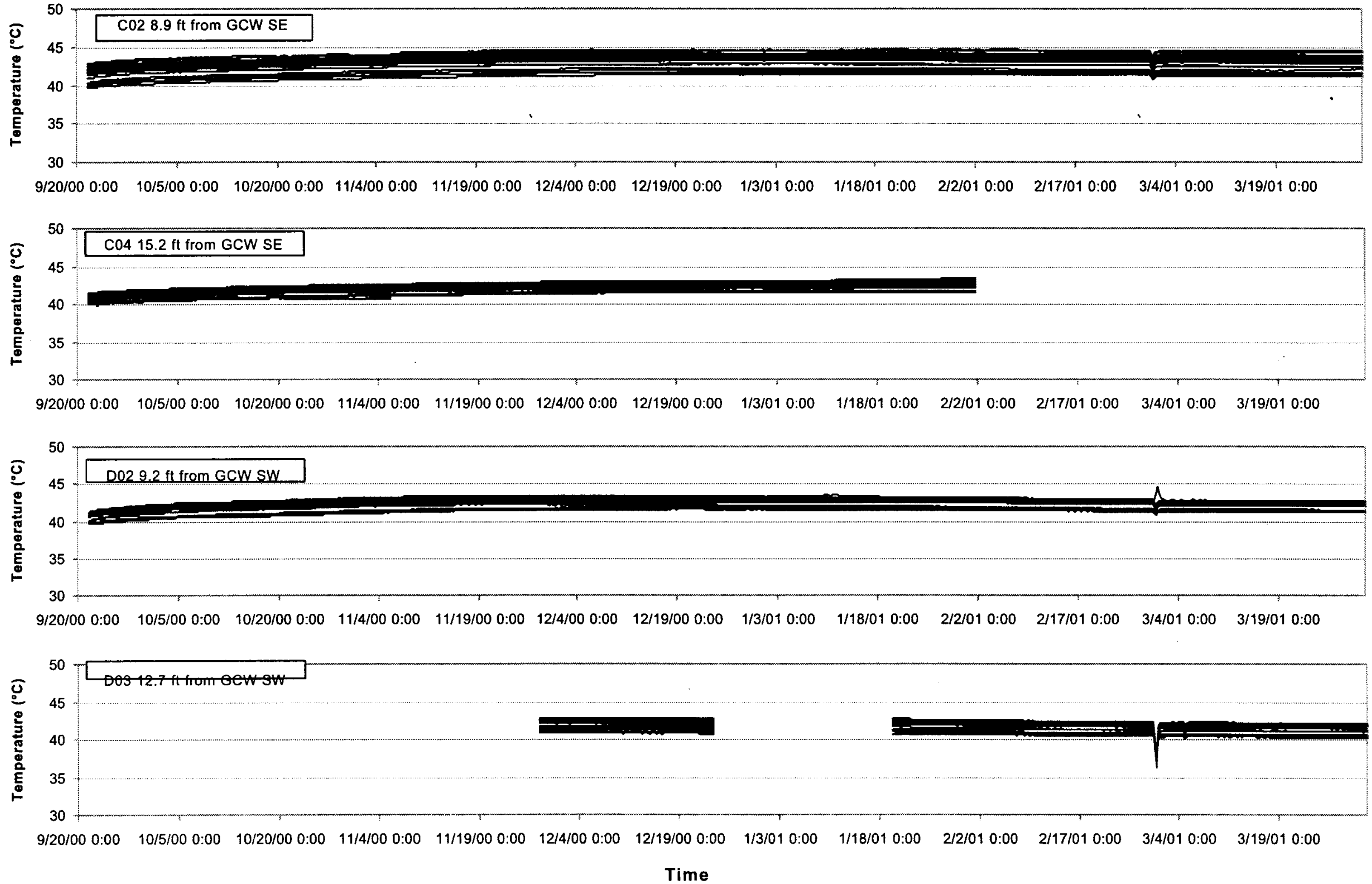


NOTES:
1) Data shown is from the post-test period from September 20, 2000 to April 1, 2001
2) Data at flow sensor C04 after February 2, 2001 were deleted. For unknown reasons, the original data contains a gradually temperature shift.
3) Data at flow sensor D03 from September 20 to November 30, 2000 and from December 20, 2000 to January 24, 2001 were deleted. The original data were affected by electrical noise.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

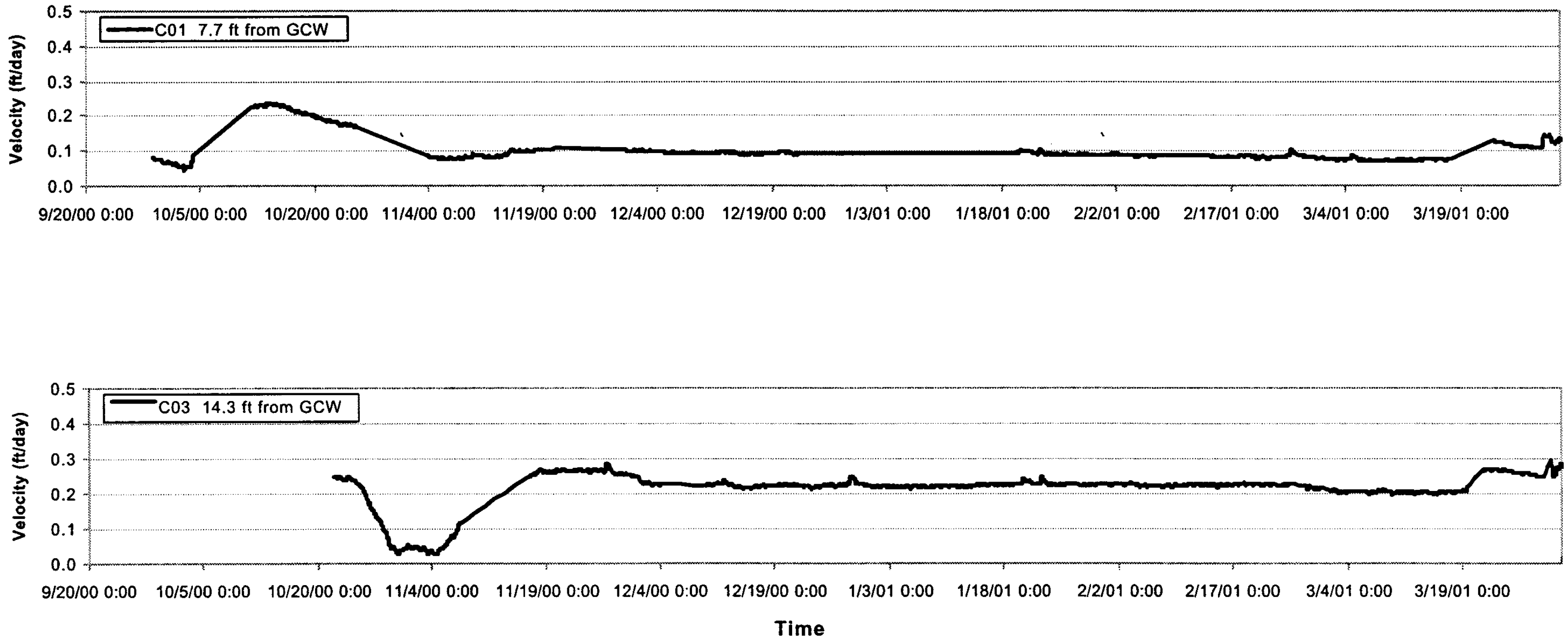
FIGURE 67
Flow Sensor Inversion Errors Versus Time in Deep Aquifer Zone
9/20/00-4/1/01

Tetra Tech EM Inc.



NOTES:
1) Data shown is from the post-test period from September 20, 2000 to April 1, 2001
2) Data at flow sensor C04 after February 2, 2001 were deleted. For unknown reasons, the original data contains a gradually temperature shift.
3) Data at flow sensor D03 from September 20 to November 30, 2000 and from December 20, 2000 to January 24, 2001 were deleted. The original data were affected by electrical noise.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA GCW TECHNOLOGY EVALUATION
FIGURE 68 **Thermistor Temperature Versus Time** **in Deep Aquifer Zone Flow Sensors** **9/20/00 - 4/1/01**
Tetra Tech EM Inc.

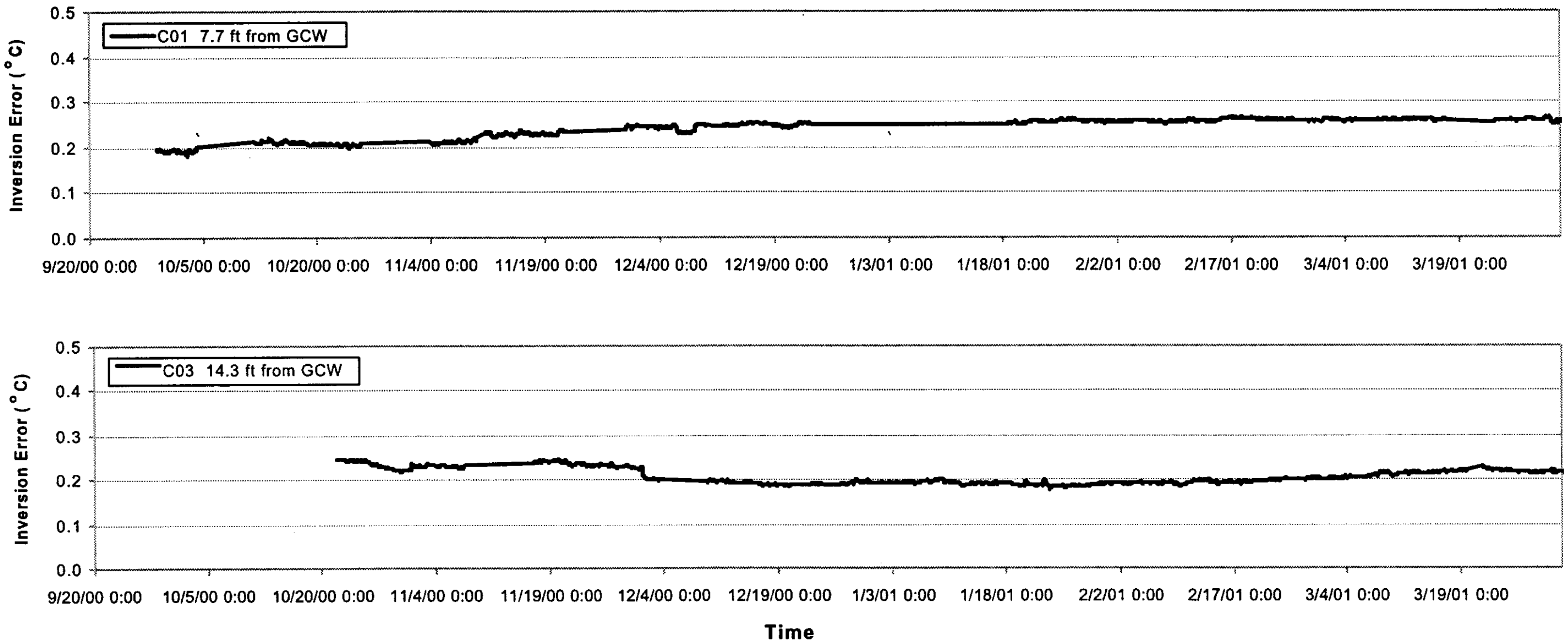


NOTES:
1) Data shown is from the post-test period from September 20, 2000 to April 1, 2001
2) Data from flow sensor D01was not used for the period shown for the period shown due to malfunction of the sensor.
3) Data at flow sensor C03 from September 20 to October 21, 2000. The original data were affected by electrical noise. The original data were affected by eletrical noise.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 69
Horizontal Groundwater Darcy Velocity Versus Time in Shallow Aquifer Zone Measured by Flow Sensors 9/20/00-4/1/01 (Actual Data)

Tetra Tech EM Inc.

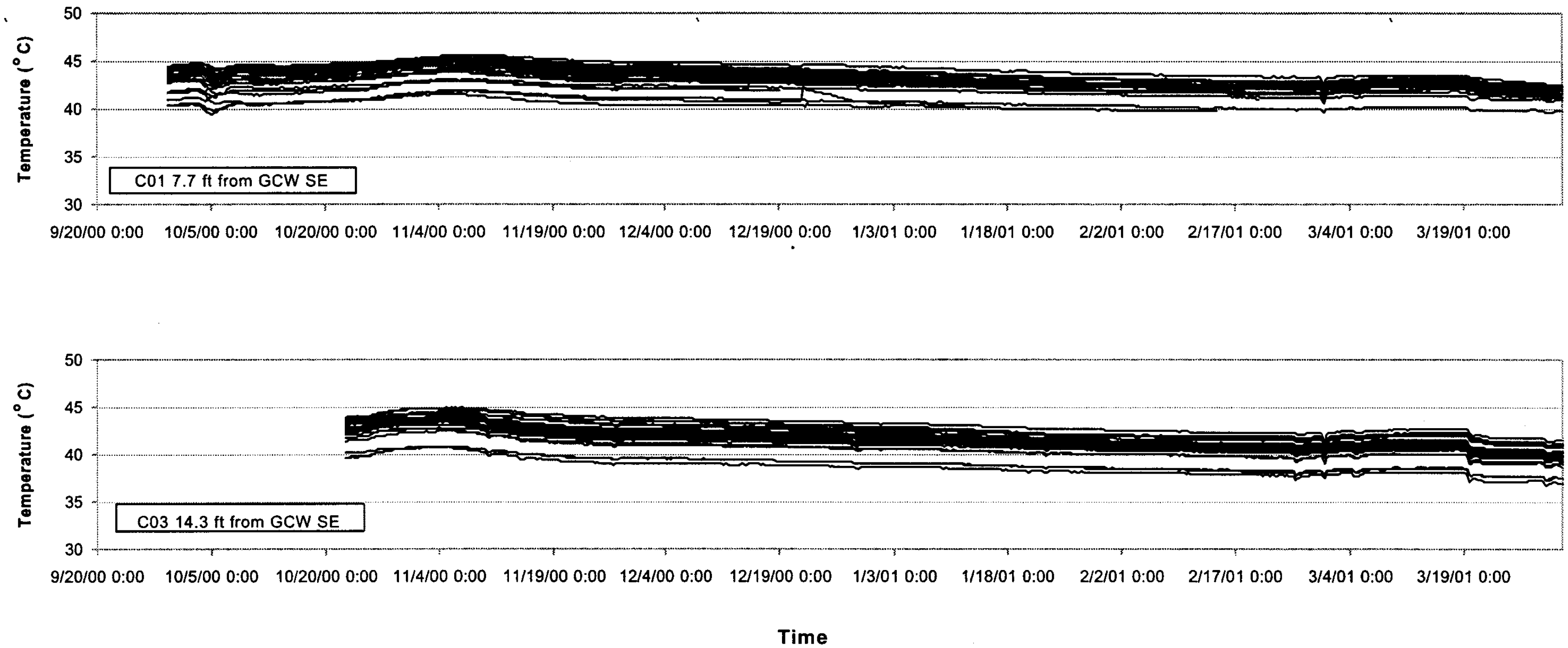


NOTES:
1) Data shown is from the post-test period from September 20, 2000 to April 1, 2001
2) Data from flow sensor D01was not used for the period shown for the period shown due to malfunction of the sensor.
3) Data at flow sensor C03 from September 20 to October 21, 2000. The original data were affected by electrical noise. The original data were affected by eletrical noise.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 70
Flow Sensor Inversion Errors Versus Time in Shallow Aquifer Zone
9/20/00-4/1/01

Tetra Tech EM Inc.

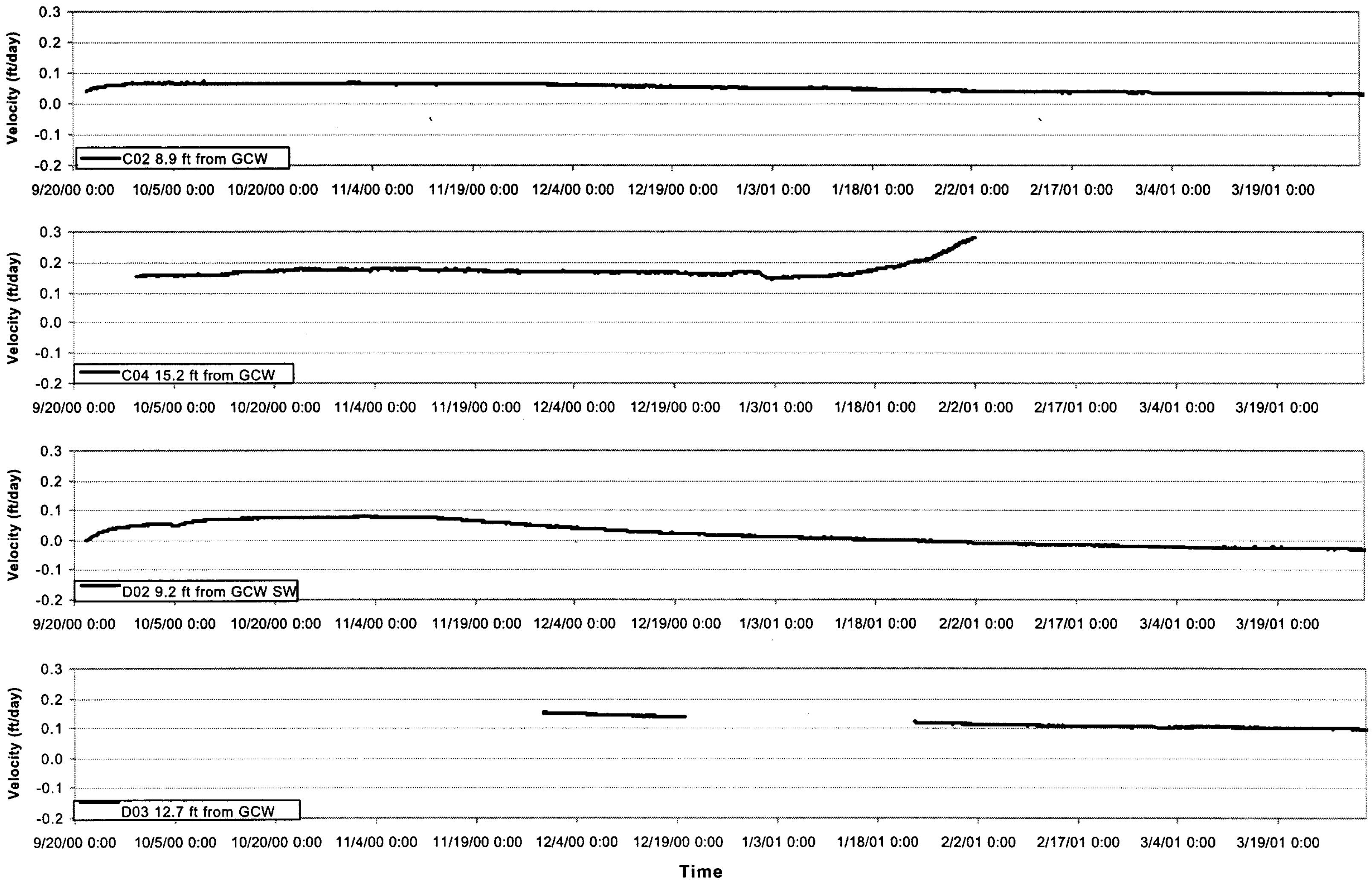


NOTES:
1) Data shown is from the post-test period from September 20, 2000 to April 1, 2001
2) Data from flow sensor D01was not used for the period shown for the period shown due to malfunction of the sensor.
3) Data at flow sensor C03 from September 20 to October 21, 2000. The original data were affected by electrical noise. The original data were affected by eletrical noise.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 71
Thermistor Temperature Versus Time in Shallow Aquifer Zone Flow Sensors 9/20/00 - 4/1/01

Tetra Tech EM Inc.

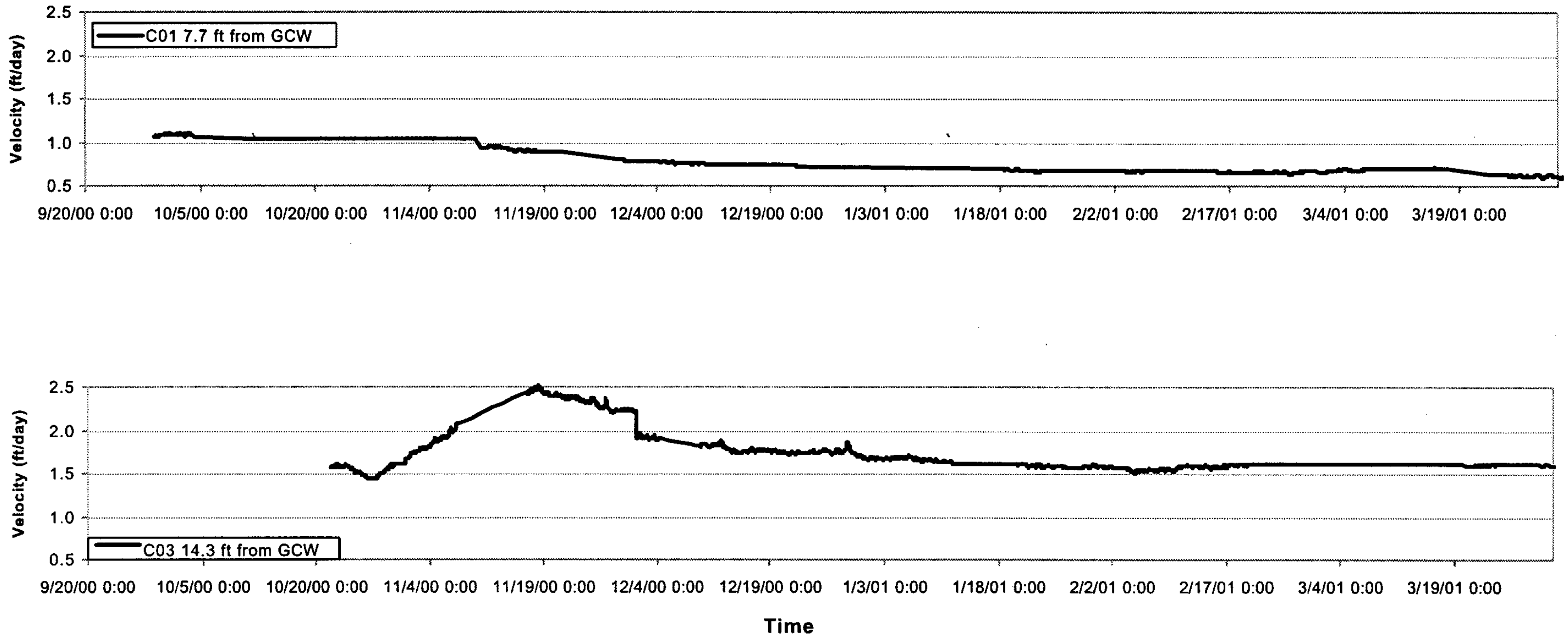


NOTES:
1) Data shown is from the post-test period from September 20, 2000 to April 1, 2001
2) Data at flow sensor C04 after February 2, 2001 were deleted. For unknown reasons, the original data contains a gradually temperature shift.
3) Data at flow sensor D03 from September 20 to November 30, 2000 and from December 20, 2000 to January 24, 2001 were deleted. The original data were affected by electrical noise.
4) Positive vertical velocity is indicative of upward hydraulic gradient.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 72
Vertical Groundwater Darcy Velocity Versus Time in Deep Aquifer Zone Measured by Flow Sensors 9/20/00-4/1/01 (Actual Data)

Tetra Tech EM Inc.

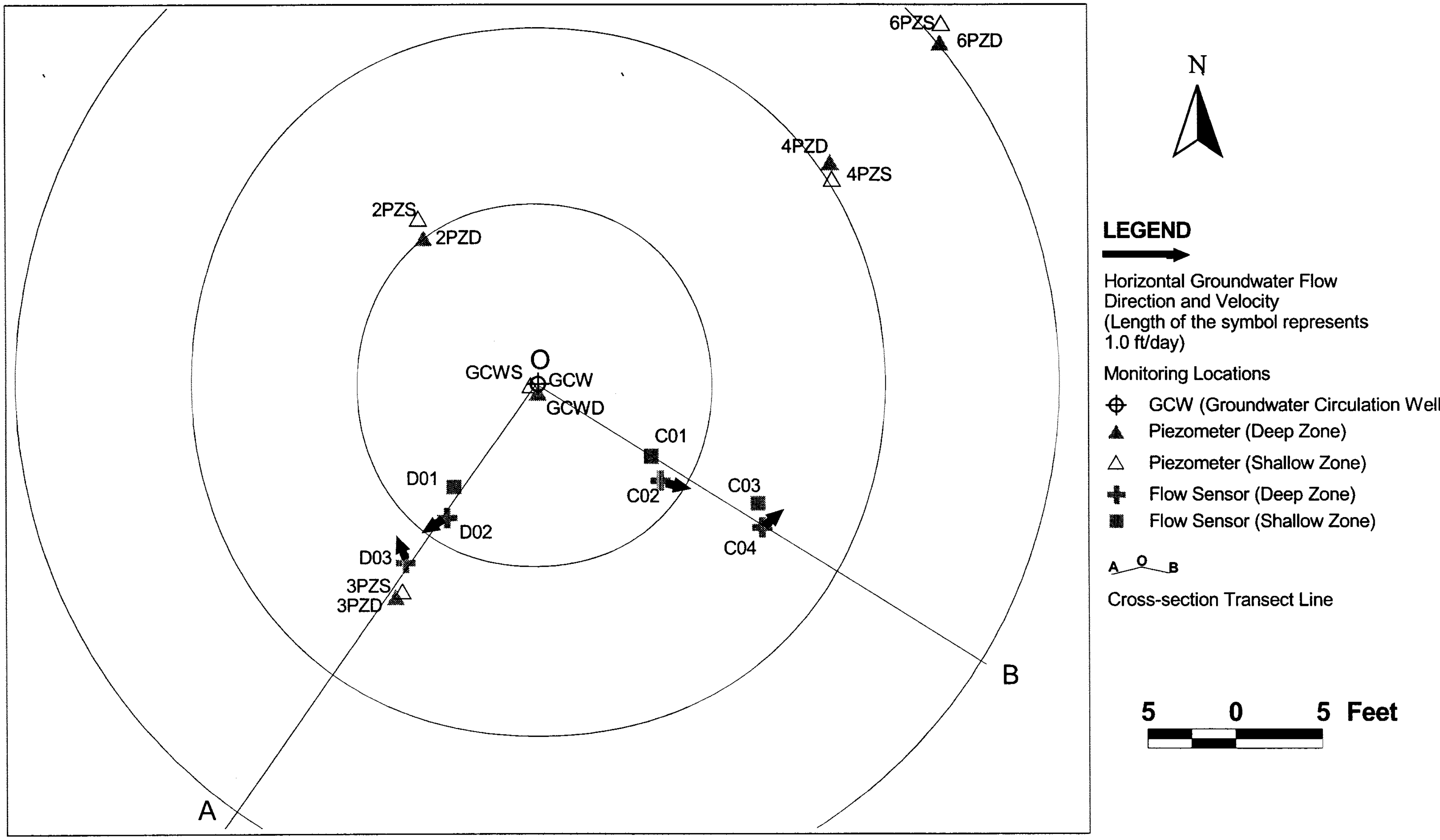


NOTES:
1) Data shown is from the post-test period from September 20, 2000 to April 1, 2001
2) Data from flow sensor D01was not used for the period shown for the period shown due to malfunction of the sensor.
3) Data at flow sensor C03 from September 20 to October 21, 2000. The original data were affected by electrical noise. The original data were affected by eletrical noise.
4) Positive vertical velocity is indicative of upward hydraulic gradient.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 73
Vertical Groundwater Darcy Velocity Versus Time in Shallow Aquifer Zone Measured by Flow Sensors 9/20/00-4/1/01 (Actual Data)

Tetra Tech EM Inc.

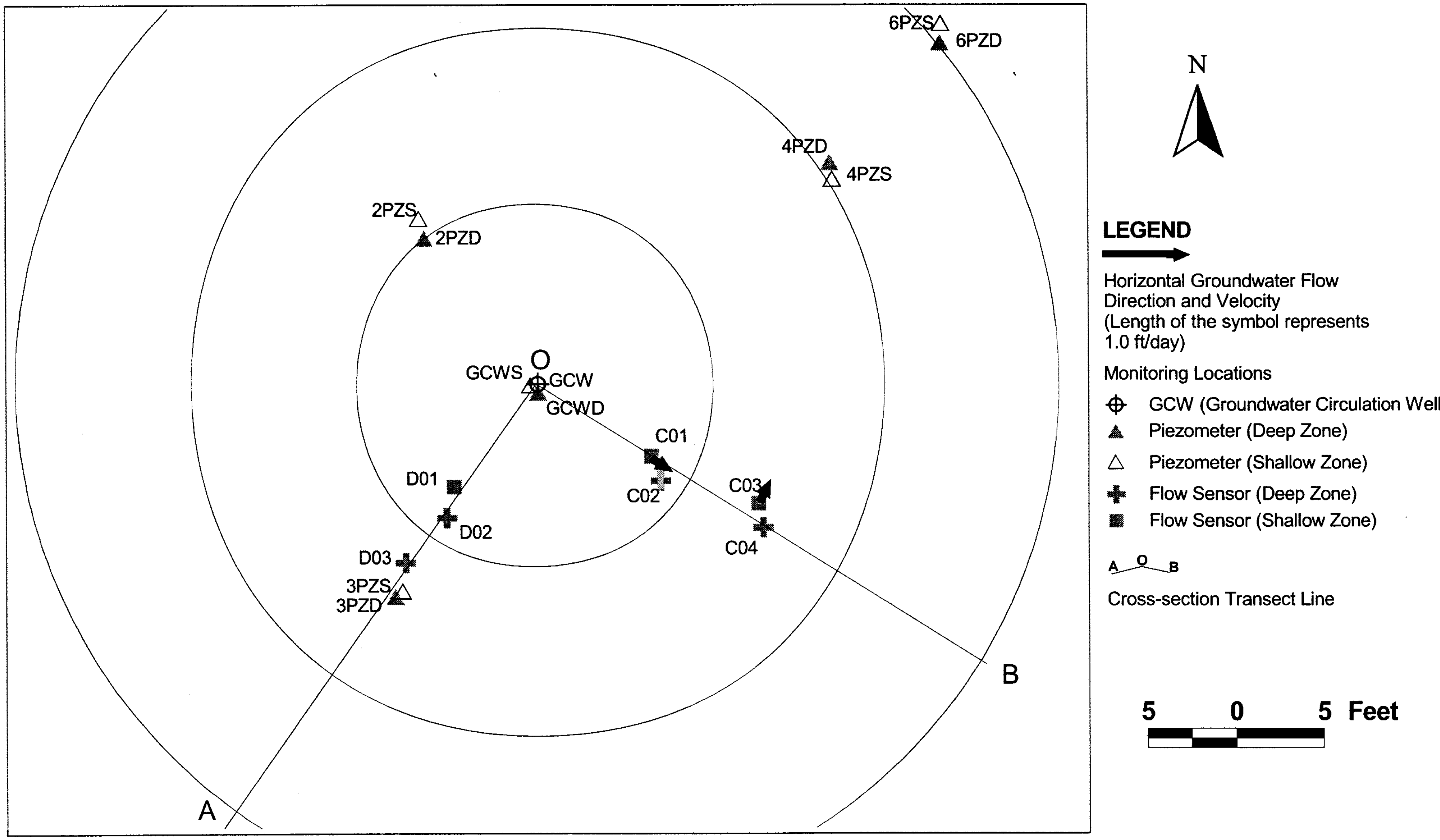


NOTES:
1) Data evaluated was collected on Feburary 2, 2001.
Flow sensor data shown is from the post-test period from September 20, 2000 to April 1, 2001.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 74
Horizontal Groundwater Darcy Velocity in Deep Aquifer Zone Measured by Flow Sensors Under Natural Flow Conditions (02/02/01)

Tetra Tech EM Inc.

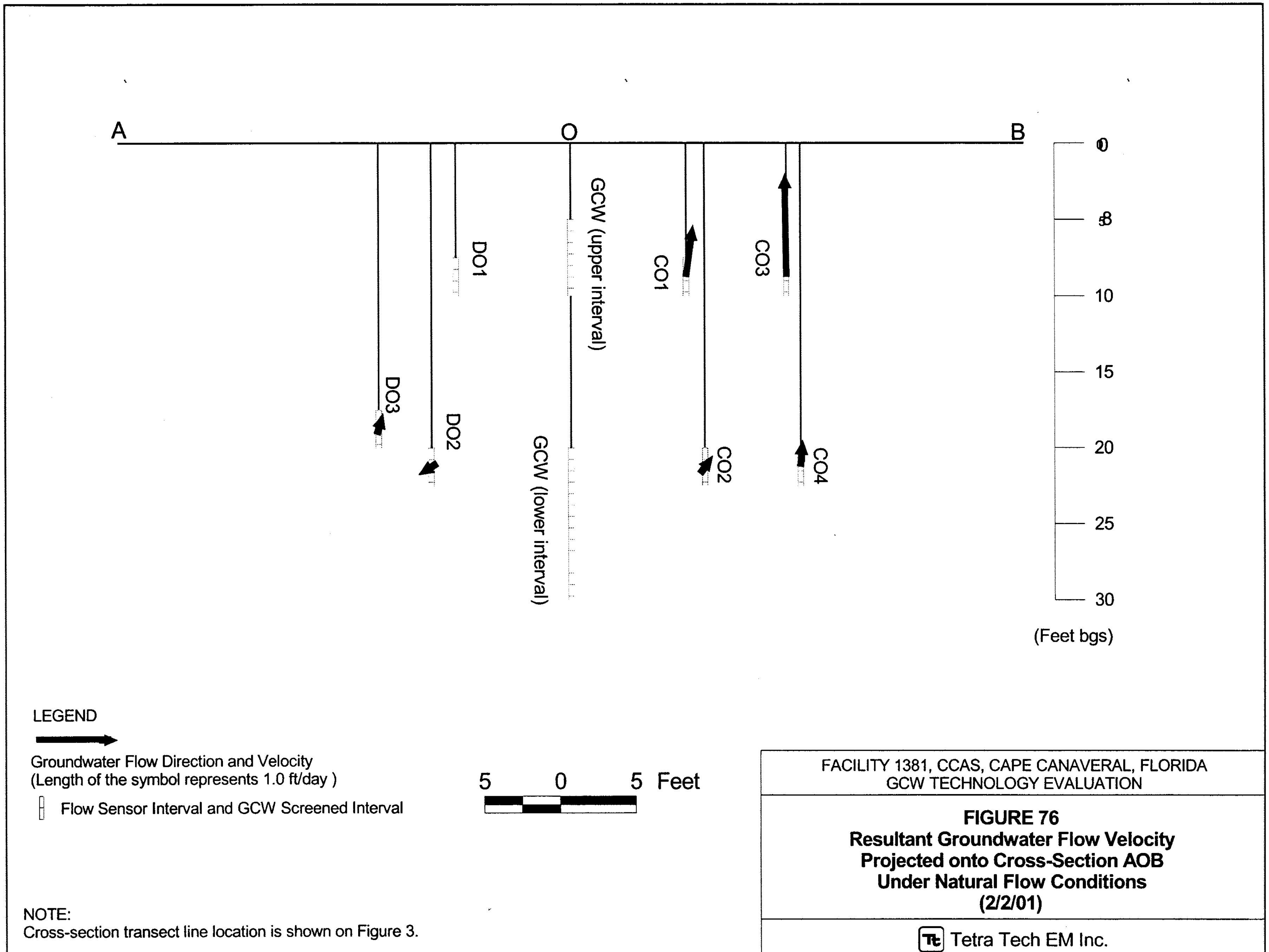


NOTES:
1) Data evaluated was collected on Feburary 2, 2001.
Flow sensor data shown is from the post-test period from September 20, 2000 to April 1, 2001.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 75
Horizontal Groundwater Darcy Velocity in Shallow Aquifer Zone Measured by Flow Sensors Under Natural Flow Conditions (02/02/01)

Tetra Tech EM Inc.



FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE 76
Resultant Groundwater Flow Velocity Projected onto Cross-Section AOB Under Natural Flow Conditions (2/2/01)

Tetra Tech EM Inc.

TABLE 1. CHRONOLOGY OF GCW FIELD ACTIVITIES
Cape Canaveral Air Station, Cape Canaveral, Florida

DATE	DESCRIPTION OF FIELD EVENT
November 22-24, 1999	GCW drilled, installed and developed
January 28–February 25, 2000	Series of short term pumping tests performed in GCW to determine pumping and treatment system performance and operating parameters for long-term test
February 29, 2000	Begin long-term pump and treat test
April 3, 2000	End long-term pump and treat test
April 11-12, 2000	GCW run in circulation mode to test system operation
April 20, 2000	Begin long-term GCW test
June 26-28, 2000	Groundwater flow sensors installed
July 1, 2000	Groundwater flow sensor data collection begins
July 28, 2000	End long-term GCW test
August 1, 2000	Minitroll pressure transducers installed in 8 piezometers
August 2, 2000	Begin final pump-and-treat test
August 29,2000	End final pump-and-treat test
September 12, 2000	Pre-Test Activities 8:00 AM to 7:00 PM
September 13, 2000	Step drawdown tests performed in GCW: Step 1 - 10:30 AM to 11:30 AM Step 2 - 11:30 AM to 12:30 PM Step 3 - 12:30 PM to 3:00 PM Step 4 - 3:00 PM to 3:30 PM Recovery started at 3:30 PM
September 14, 2000	Dipole Flow Tests 1 through 5 conducted in GCW: Dipole Test 1 – 11:00 AM to 11:30 AM Dipole Test 2 – 12:00 PM to 12:30 PM Dipole Test 3 – 1:00 PM to 1:30 PM Dipole Test 4 – 2:00 PM to 2:30 PM Dipole Test 5 – 3:00 PM to 4:30 PM

TABLE 1. CHRONOLOGY OF GCW FIELD ACTIVITIES (continued)
Cape Canaveral Air Station, Cape Canaveral, Florida

DATE	DESCRIPTION OF FIELD ACTIVITY
September 15, 2000	Begin constant rate pumping test at 8:00 AM
September 16, 2000	End constant rate pumping test at 1:00 PM
September 18, 2000	End constant rate pumping test recovery period at 7:59 AM
September 18, 2000	Dipole Flow Tests 6 and 7 conducted in GCW: Dipole Test 6 – 8:00 AM to 10:22 AM Dipole Test 7 – 2:00 PM to 8:00 PM
September 19, 2000 to present	Continuous groundwater flow sensor data collection

TABLE 2. GROUNDWATER FLOW DIRECTIONS UNDER NATURAL FLOW CONDITIONS
Cape Canaveral Air Station, Cape Canaveral, Florida

DATE (1)	SHALLOW AQUIFER ZONE	DEEP AQUIFER ZONE
April 6-7, 2000	WEST/NORTH	WEST/NORTH
June 15, 2000	SOUTH/SOUTHEAST	SOUTH/EAST
June 27, 2000	WEST	SOUTHEAST
July 7, 2000	SOUTH/EAST	NORTH/NORTHWEST
September 13, 2000	NORTHWEST	NORTHEAST/SOUTHWEST (2)
September 14, 2000	NORTHWEST	SOUTH/SOUTHEAST
September 15, 2000	NORTHWEST	SOUTH/SOUTHEAST
September 18, 2000	NORTHWEST	NORTHEAST/SOUTHWEST (2)

Notes:
1) Groundwater flow directions determined using water level elevations measured by hand.
2) Possible groundwater flow divide in the vicinity of the GCW indicated by the data.

TABLE 3. GROUNDWATER ELEVATION DATA
Cape Canaveral Air Station, Cape Canaveral, Florida

Well ID	Ground Elevation (feet NGVD)	TOC Elevation (feet NGVD)	Depth to Water (9/13/00, 8:50 AM)	Groundwater Elevation (9/13/00, 8:50 AM)	Depth to Water (9/14/00, 8:40 AM)	Groundwater Elevation (9/14/00, 8:40 AM)	Depth to Water (9/15/00, 7:30 AM)	Groundwater Elevation (9/15/00, 7:30 AM)	Depth to Water (9/18/00, 7:30 AM)	Groundwater Elevation (9/18/00, 7:30 AM)
GCWD	9.37	10.40	8.87	1.53	8.85	1.55	8.84	1.56	8.67	1.73
GCWS	9.57	12.40	10.87	1.53	10.85	1.55	10.84	1.56	10.66	1.74
2PZD	9.78	10.19	8.67	1.52	8.63	1.56	8.64	1.55	8.48	1.71
2PZS	9.73	9.98	8.51	1.47	8.47	1.51	8.48	1.50	8.32	1.66
3PZD	9.39	9.88	8.45	1.43	8.38	1.50	8.35	1.53	8.24	1.64
3PZS	9.35	9.73	8.21	1.52	8.19	1.54	8.18	1.55	8.01	1.72
4PZD	9.40	9.77	8.25	1.52	8.21	1.56	8.21	1.56	8.05	1.72
4PZS	9.40	9.75	8.23	1.52	8.20	1.55	8.20	1.55	8.04	1.71
6PZD	8.63	8.99	7.51	1.48	7.48	1.51	7.17	1.82	7.33	1.66

Notes:
1) Piezometer 6PZS was not used to obtain water level elevation data during the aquifer testing period.
2) Groundwater elevation data measurements presented in the table were collected assuming static conditions.

TABLE 4. SUMMARY OF IN-SITU GROUNDWATER VELOCITY SENSOR SPECIFICATIONS
Cape Canaveral Air Station, Cape Canaveral, Florida

Flow Sensor Parameter Description	Specification
Operating Range	0.01 to 2.0 feet/day
Accuracy	0.01 feet/day
Resolution	0.001 feet/day
Sensor Length	30 inches
Sensor Outside Diameter	2 3/8 inches
Power Required	57 Volts at 1.4 amps
Data Output	0-2500 mV
Data Collection Equipment	CR10 data logger
Data Processing	HTFLOW software
Life Span	1-2 years
Maximum Installation Depth	>400 feet below ground surface

TABLE 5. GROUNDWATER FLOW SENSOR INSTALLATION SPECIFICATIONS
Cape Canaveral Air Station, Cape Canaveral, Florida

Flow Sensor ID	Flow Sensor Location (distance from GCW)	Flow Sensor Installation Depth (feet bgs)	Aquifer Zone	TOC Elevation (feet above NGVD)	Ground Elevation (1) (feet above NGVD)
C01	7.67 feet to southeast	8.8 to 11.0	Shallow	9.46	9.20
C02	8.90 foot to southeast	19.3 to 21.5	Deep	9.46	9.23
C03	14.30 feet to southeast	8.3 to 10.5	Shallow	9.31	9.15
C04	15.22 feet to southeast	19.3 to 21.5	Deep	9.39	9.14
D01	7.59 feet to southwest	8.8 to 11.0	Shallow	9.66	9.39
D02	9.24 feet to southwest	16.8 to 19.0	Deep	9.61	9.43
D03	12.73 feet to southwest	17.3 to 19.5	Deep	9.73	9.38

Notes:

(1)	Ground elevation at flow sensor location
GCW	Groundwater circulation well
bgs	Below ground surface
TOC	Top of casing
NGVD	National Geodetic Vertical Datum of 1929

TABLE 6. GROUNDWATER FLOW VELCITIES AND FLOW DIRECTION MEASURED BY FLOW SENSORS
Cape Canaveral Air Station, Cape Canaveral, Florida

Flow Sensor ID and Measured Parameters	July 2000 (7/1-7/31/00)	August 2000 (8/1-8/31/00)	Aquifer Testing (9/13-9/19/00)				Post-Test Period (9/20/00-4/01/01)
	Long Term GCW Circulation Test	Final Pump and Treat Test	End of Constant Rate Pumping Test	End of Pumping Test Recovery	End of Dipole Test 6	End of Dipole Test 7	Representative Flow, Post Test Period
	7/28/00, 16:00 (1)	*8/25/00. 0:00 (1)*	*9/16/00, 12:30 (1)*	*9/18/00, 7:30 (1)*	*9/18/00, 10:30 (1)*	*9/18/00, 20:00 (1)*	*2/02/01, 0:00 (1)*
	Corrected Data (5)	*Corrected Data (5)*	*Corrected Data (5)*	*Actual Data (6)*	*Corrected Data (5)*	*Corrected Data (5)*	*Actual Data (6)*
Shallow Flow Sensors							
C01 horizontal velocity (2)	0.35	0.22	0.26	0.35	0.37	0.43	0.088
C01 vertical velocity (2,3)	**-2.49**	**-0.38**	**-0.55**	0.71	**-0.96**	**-1.39**	0.664
C01 horizontal flow dir. (4)	121	338	341	81	125	126	122
C03 horizontal velocity (2)	1.62	0.22	0.36	0.47	0.36	0.78	0.213
C03 vertical velocity (2,3)	**-0.27**	**-1.47**	**-0.3**	1.21	**-0.72**	**-0.73**	1.51
C03 horizontal flow dir. (4)	106	280	309	43	96	90	27
D01 horizontal velocity (2)	2.08	0.43	0.76	0.64	2.19	2.17	ND (5)
D01 vertical velocity (2,3)	**-5.55**	**-0.09**	**-0.68**	1.48	**-0.83**	**-3.15**	ND (5)
D01 horizontal flow dir. (4)	196	333	334	46	206	206	ND (5)
Deep Flow Sensors							
C02 horizontal velocity (2)	1.22	0.57	0.94	0.05	0.49	0.85	0.029
C02 vertical velocity (2,3)	**-4.85**	**-1.65**	**-2.81**	0.02	**-1.52**	**-2.82**	0.039
C02 horizontal flow dir. (4)	298	303	302	31	300	302	102
C04 horizontal velocity (2)	0.47	0.32	0.59	0.01	0.54	0.64	0.057
C04 vertical velocity (2,3)	**-0.29**	**-0.2**	**-0.33**	0.09	**-0.09**	**-0.32**	0.268
C04 horizontal flow dir. (4)	327	326	328	71	330	328	50
D02 horizontal velocity (2)	0.87	0.8	0.89	0.08	0.56	0.83	0.056
D02 vertical velocity (2,3)	**-0.13**	**-0.26**	**-0.03**	**-0.07**	0.07	**-0.2**	**-0.032**
D02 horizontal flow dir. (4)	69	70	68	66	67	67	238
D03 horizontal velocity (2)	1.69	0.78	1.74	0.06	1.32	1.51	0.042
D03 vertical velocity (2,3)	**-1.76**	**-0.79**	**-1.66**	0.05	**-0.53**	**-0.81**	0.08
D03 horizontal flow dir. (4)	334	337	333	329	331	332	339

Notes:

(1) Actual data selection times may vary slightly due to different data collection time intervals.
(2) Horizontal and vertical velocity values are in feet per day.
(3) Positive values indicate upward vertical velocities, and negative values (in bold) indicate downward velocities.
(4) Horizontal flow directions are presented as azimuths, reading in degrees clockwise from north.
(5) Corrected data is flow sensor data with background removed using a small simulation window.
(6) Actual data is the original flow sensor data with a small simulation window that has not been corrected for background.

TABLE 7. GCW OPERATIONAL EVENTS IN JULY-AUGUST 2000 DETERMINED FROM FLOW SENSOR DATA
Cape Canaveral Air Station, Cape Canaveral, Florida

DATE	TIME	PROBABLE GCW OPERATION AS RECORDED BY FLOW SENSORS
Long-Term GCW Circulation Test		
July 10, 2000	9:00 to 10:01 AM	Pump turned on for 61 minutes
July 10, 2000	4:30 PM	Pumping started
July 14, 2000	8:48 AM	Pumping stopped
July 14, 2000	10:46 AM	Pumping started
July 28, 2000	4:30 PM	Pumping stopped
Final Pump-and-Treat Test		
August 1, 2000	2:48 to 3:45 PM	Pump turned on for 57 minutes.
August 2, 2000	9:45 AM	Pumping started
August 4, 2000	4:46 PM	Pumping stopped
August 15, 2000	8:48 AM	Pumping started
August 16, 2000	11:48 PM	Pumping stopped
August 17, 2000	8:48 AM	Pumping started
August 18, 2000	9:45 PM	Pumping stopped
August 18, 2000	1:46 PM	Pumping started
August 19, 2000	12:45 AM	Pumping stopped
August 21, 2000	7:46 AM	Pumping started
August 25, 2000	8:48 AM	Pumping stopped
August 25, 2000	2:48 PM	Pumping started
August 25, 2000	10:46 PM	Pumping stopped
August 28, 2000	8:48 AM	Pumping started
August 28, 2000	3:45 PM	Pumping stopped
August 29, 2000	7:46 AM	Pumping started
August 29, 2000	3:45 PM	Pumping stopped

TABLE 8. REPRODUCIBILITY SUMMARY
Cape Canaveral Air Station, Cape Canaveral, Florida

Sensor	Long-Term GCW Operation		Final Pump-and-Treat Operation		Aquifer Hydraulic Test Operation		Post Operation	
	Average Horizontal Velocity RPD (%)	Average Vertical Velocity RPD (%)	Average Horizontal Velocity RPD (%)	Average Vertical Velocity RPD (%)	Average Horizontal Velocity RPD (%)	Average Vertical Velocity RPD (%)	Average Horizontal Velocity RPD (%)	Average Vertical Velocity RPD (%)
Deep Aquifer Zone Flow Sensors								
C02	0.2	0.4	0.7	1.5	0.9	0.1	1.6	0.8
C04	0.3	0.5	0.5	14	0.6	1.0	2.3	0.4
D02	0.1	1.0	0.3	5.1	0.3	0.9	1.5	3.8
D03	0.2	0.1	0.3	2.2	6.7	23.2	2.6	0.6
Shallow Aquifer Zone Flow Sensors								
C01	0.2	0.5	0.7	0.3	0.4	1.3	0.8	0.2
C03	0.4	0.2	1.0	10.0	0.8	0.1	1.0	0.3
D01	0.2	0.5	0.5	0.5	2.4	3.9	NA	NA

Notes:
GCW Groundwater Circulation Well
RPD Relative percent difference = $[V1 - V2/\{0.5*(V1+V2)\}]*100$
V_1 Initial velocity measurement
V_2 Subsequent velocity measurement
NA Reproducibility data not available
% Percent

APPENDIX A

HYDROGEOLOGICAL INVESTIGATION REPORT

of the

AQUIFER TREATED BY THE WASATCH GROUNDWATER CIRCULATION WELL SYSTEM

CAPE CANAVERAL AIR STATION
CAPE CANAVERAL, FLORIDA

Prepared for

U.S. Environmental Protection Agency
National Risk Management Research Laboratory
Superfund Innovative Technology Evaluation Program
Cincinnati, Ohio

Prepared by

Tetra Tech EM Inc.
San Diego, California

September 26, 2001

APPENDIX A
HYDROGEOLOGICAL INVESTIGATION REPORT
TABLE OF CONTENTS

FIGURES

TABLES

ACRONYMS AND ABBREVIATIONS

bgs	Below ground surface
cm/sec	Centimeters per second
CCAS	Cape Canaveral Air Station
DCA	Dichloroethane
DCE	Dichloroethene
DFT	Dipole flow test
DNAPL	Dense nonaqueous phase liquid
Eh	Reduction/oxidation potential
EPA	U. S. Environmental Protection Agency
ft/day	Feet per day
ft/ft	Feet per foot
ft^2/day	Square feet per day
GCW	Groundwater circulation well
gpm	Gallons per minute
gpm/ft	Gallons per minute per foot
g/cm^3	Grams per cubic centimeter
IR	Installation Restoration
KSC	John F. Kennedy Space Center
mg/kg	Milligrams per kilogram
mg/L	Milligrams per liter
MLLW	Mean lower low water
msl	Mean sea level
mv	Millivolts
NOAA	National Oceanic and Atmospheric Administration
NTU	Nephelometric turbidity units
ORD	Office of Research and Development
OSWER	Office of Solid Waste and Emergency Response
PAH	Polynuclear aromatic hydrocarbon
PCE	Tetrachloroethene
psi	Pounds per square inch
PVC	Polyvinyl chloride
scfm	Standard cubic feet per minute
SARA	Superfund Amendments and Reauthorization Act
SITE	Superfund Innovative Technology Evaluation
TCE	Trichloroethene

ACRONYMS AND ABBREVIATIONS (continued)

Tetra Tech	Tetra Tech EM Inc.
VOC	Volatile organic compound
WEI	Wasatch Environmental, Inc.
µg/L	Micrograms per liter
µmhos/cm	Micromhos per centimeter

EXECUTIVE SUMMARY

In support of the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program, Tetra Tech EM Inc. (Tetra Tech), evaluated the circulation cell generated by the groundwater circulation well (GCW) technology designed by Wasatch Environmental, Inc. (WEI) of Salt Lake City, Utah. The GCW is a dual-screened, in-well air stripping system designed to remove volatile organic compounds (VOCs) from groundwater and is being operated by Parsons Engineering Science at Facility 1381 at the Cape Canaveral Air Station (CCAS) in Cape Canaveral, Florida on behalf of the Air Force Center of Environmental Excellance (AFCEE).

A series of aquifer hydraulic tests were conducted to assess the hydrogeological characteristics of the aquifer where the GCW was installed to assist in evaluating the radius of influence created by the GCW. The aquifer hydraulic tests included (1) a step drawdown test in the lower screened interval of the GCW, (2) a dipole flow test with pumping from the lower screened interval of the GCW and reinjection in the upper screened interval of the GCW, and (3) a long-term constant rate discharge pumping test in the lower screened interval of the GCW.

The aquifer hydraulic tests were conducted to obtain information to assess hydraulic communication among various portions of the aquifer beneath the site, as well as to estimate hydraulic parameters of the aquifer, such as hydraulic conductivity, transmissivity, storativity, and anisotropy. In addition, the aquifer tests provided information on efficiencies of the two-screened intervals of the GCW.

The aquifer hydraulic testing was conducted using the GCW as the pumping well. The GCW consists of a 6-inch diameter outer casing; the upper portion of the GCW is screened from 5 to 10 feet below ground surface (bgs), and the lower portion of the GCW is screened from 20 to 30 feet bgs. Inflatable packers were used to isolate and facilitate pumping from each screened interval separately. A network of piezometers installed in the shallow and deep portions of the aquifer was used as observation wells during the aquifer tests.

A series of aquifer hydraulic tests was conducted to assess the hydrogeological characteristics of the surficial aquifer where the GCW is installed. Data collected during the aquifer tests from groundwater flow sensors installed adjacent to the GCW were used to evaluate the extraction and recirculating flow patterns and capacity of the GCW. The aquifer hydraulic tests included (1) a step drawdown test in the lower screened interval, (2) dipole flow tests with pumping from the lower screened interval and injecting into the upper screened interval, and (3) a constant rate discharge pumping test using the lower screened interval as the pumping well.

The dipole flow test (DFT), a new single-well hydraulic test for aquifer characterization, was first proposed by Kabala (1993) and was designed to characterize the vertical distribution of local horizontal and vertical hydraulic conductivities near the test well. The purpose of dipole testing is to determine the aquifer anisotropic ratio. Data from the dipole flow tests performed using the GCW were used to calculate an aquifer anisotropy ratio. The average anisotropic ratio at CCAS was approximately 10 but is subject to local aquifer heterogeneities

Aquifer hydraulic testing and data analysis yielded the following results:

- The calculated aquifer transmissivity ranges from approximately 1,790 to 2,190 square feet per day (ft^2/day) (166 m^2/day to 203.3 m^2/day) based on analysis using the Hantush-Jacob (1955) model. This result is considered higher than the average transmissivity of the deep aquifer zones because of significant recharge (that is, more than normal leakage) from the shallow aquifer zone.
- The aquifer hydraulic conductivity, calculated using the transmissivities obtained previously and based on an estimated saturated aquifer thickness of 41.7 feet (12.7m), ranges from 42.9 to 52.5 feet (1.5×10^{-4} to 1.9×10^{-4} cm/s) per day.
- The transmissivity of the deep aquifer zone, as calculated from dipole test data using the Neuman (1974) delayed yield model, ranges from 196 to 337 ft^2/day (18 to 31 m^2/day).
- The estimated aquifer storativity ranges from 0.03 to 0.07, a typical range for average specific yield and storativity of an unconfined aquifer.
- The specific yield of the aquifer tested ranges from 0.06 to 0.09 based on the Neuman model for calculation of delayed yield. The storativity values from Neuman's model range from 0.006 to 0.007.
- The average anisotropic ratio at CCAS was approximately 2.4 but is subject to localized aquifer heterogeneities

1.0 INTRODUCTION

In support of the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program, Tetra Tech EM Inc. (Tetra Tech), is evaluating the performance of the groundwater circulation well (GCW), a dual-screened, in-well air-stripping system designed to remove volatile organic compounds (VOCs) from groundwater. The GCW is installed at Facility 1381 at the Cape Canaveral Air Station (CCAS) in Cape Canaveral, Florida (Figures A1 and A2). The GCW was designed by Wasatch Environmental, Inc. (WEI) of Salt Lake City, Utah, and is being operated by Parsons Engineering Science Inc. (Parsons).

A series of aquifer hydraulic tests were conducted to assess the hydrogeological characteristics of the surficial aquifer where the GCW is installed to assist in evaluating the radius of influence created by the GCW. In addition, data collected during the aquifer tests from groundwater flow sensors installed near the GCW were used to evaluate the radius of influence of the GCW.

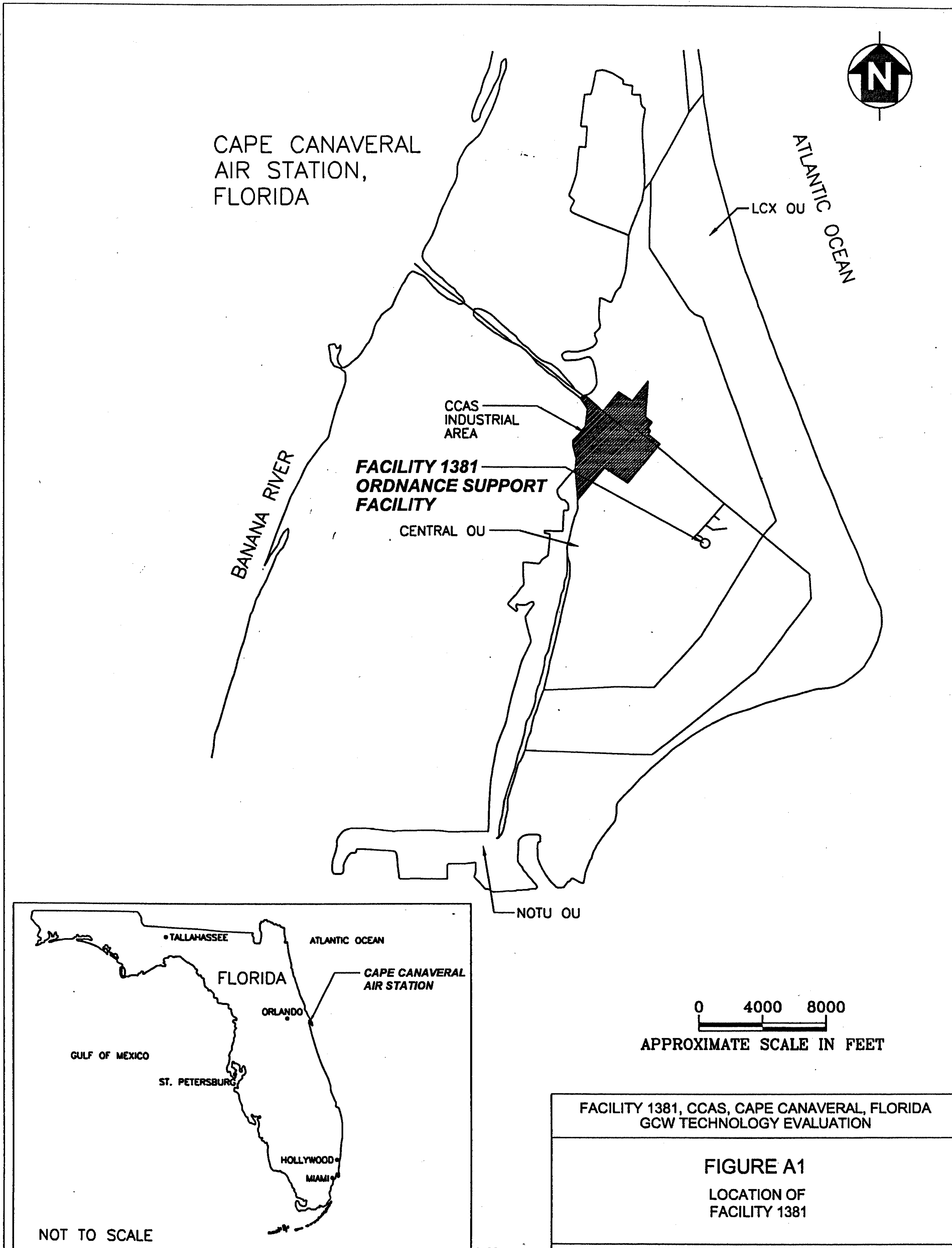
1.1 SITE PROGRAM

EPA's Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) created the SITE Program in response to the Superfund Amendments and Reauthorization Act of 1986 (SARA). The SITE Program promotes the development, evaluation, and use of new or innovative technologies to clean up Superfund sites across the country.

The primary purpose of the SITE Program is to maximize the use of alternatives in cleaning up hazardous waste sites by encouraging development and evaluation of innovative treatment and monitoring technologies. It consists of three major elements:

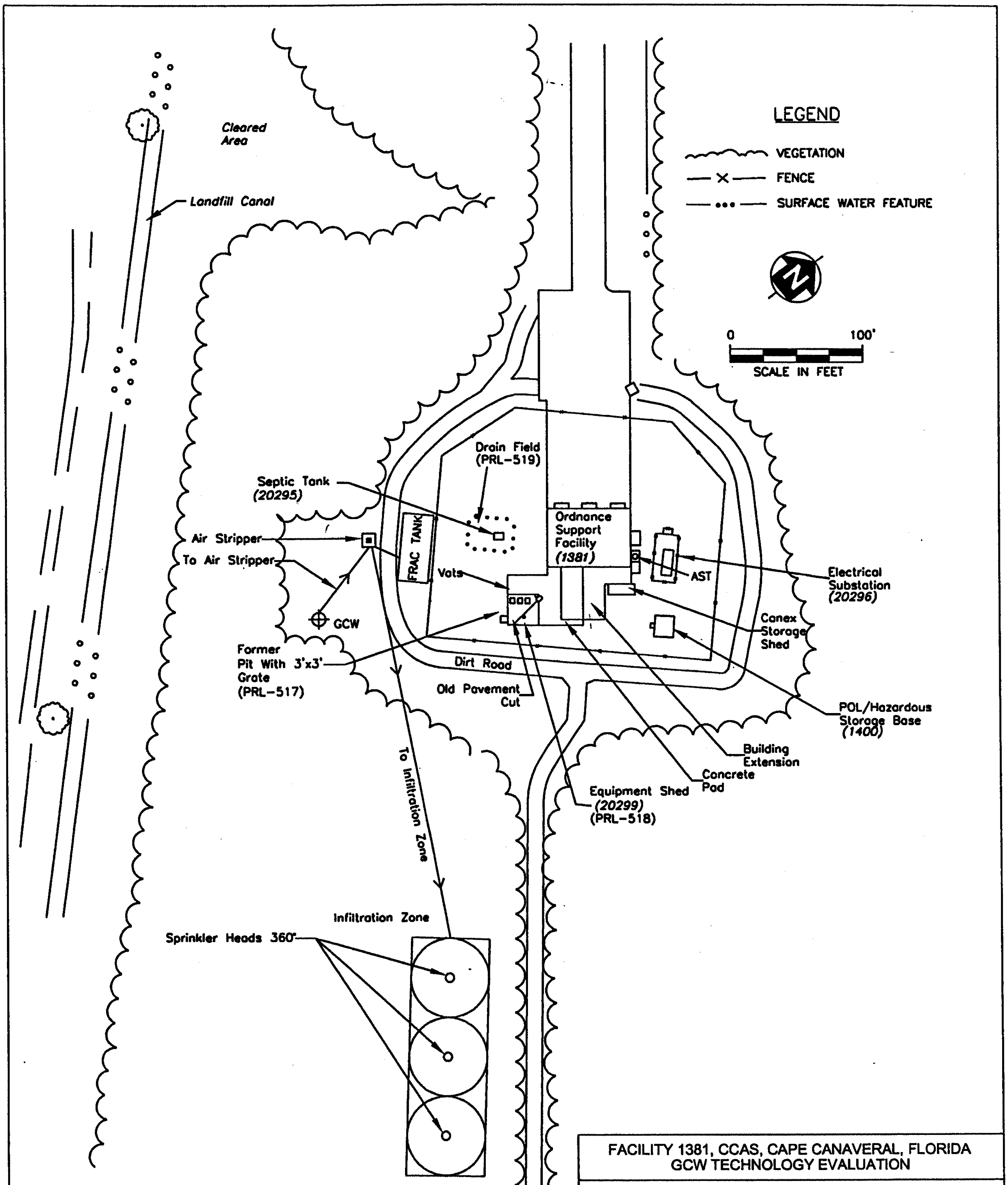
- The Technology Evaluation Program
- The Monitoring and Measurement Technologies Program
- The Technology Transfer Program

The objective of the Technology Evaluation Program is to develop reliable data on performance and cost for innovative technologies so that potential users may assess the technology's site-specific applicability. Technologies evaluated are either currently available or are about to become available for remediation of



Source: Parsons 2000.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA GCW TECHNOLOGY EVALUATION
FIGURE A1 LOCATION OF FACILITY 1381
TETRA TECH EM INC.



FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE A2
SITE MAP

TETRA TECH EM INC.

Superfund sites. SITE evaluations are conducted at hazardous waste sites under circumstances that closely simulate full-scale remediation conditions, thus ensuring the usefulness and reliability of information collected. Data collected are used to assess: (1) the performance of the technology, (2) the potential need for pre- and post-treatment processing of wastes, (3) potential operating problems, and (4) approximate costs. The evaluations also allow for assessment of long-term risks.

Existing technologies that improve field monitoring and site characterization are identified in the Monitoring and Measurement Technologies Program. This program supports new technologies that provide faster, more cost-effective contamination and site assessment data. The Monitoring and Measurement Technologies Program also formulates protocols and standard operating procedures for evaluation methods and equipment.

The Technology Transfer Program disseminates technical information on innovative technologies in the Evaluation and Monitoring and Measurements Technologies Programs through various activities. These activities increase the awareness and promote the use of innovative technologies for assessment and remediation at Superfund sites. The goal of technology transfer is to develop communication among environmental professionals who require up-to-date technical information.

1.2 OBJECTIVES OF PROJECT

Tetra Tech's primary objective in conducting the technology evaluation was as follows:

- Evaluate the extent of the circulation cell of the GCW

Tetra Tech's secondary objectives in conducting the technology evaluation are as follows:

- Evaluate the precision of the groundwater flow sensors
- Evaluate the three-dimensional groundwater flow that surrounds the GCW
- Document the operating parameters of the GCW
- Document the hydrogeologic characteristics at Facility 1381

2.0 BACKGROUND

This section describes the GCW and the associated groundwater monitoring system at CCAS. This section also provides information on site conditions, including site history, topography, geology, hydrogeology, and contamination in soil and groundwater. In addition, this section identifies the locations and describes the construction of wells installed to investigate the hydrogeology of the site.

2.1 THE GCW SYSTEM

This section provides a general description of the GCW at CCAS and describes the groundwater monitoring system for evaluating the performance of the GCW system. Table A1 provides a chronology of field activities associated with the GCW.

2.1.1 General Description

The WEI GCW system is an in situ groundwater remediation technology designed to circulate groundwater in the aquifer and strip VOCs from groundwater in place. In the WEI system, groundwater is pumped from a screen in the lower section of the well by airlift pumping. The airlift pump also introduces air into the bottom of the well using a blower. Groundwater is lifted along with the air to an upper screen, where the groundwater is then discharged back into the aquifer. As this process occurs, VOCs are stripped out of the groundwater and into the air stream. The air stream is extracted from the wellhead and is treated before it is released to the atmosphere. Groundwater that reenters the aquifer via the top screen can flow vertically downward and be recaptured by the GCW, where it is then treated again. The groundwater flow regime that develops is termed a circulation cell, and its characteristics are critical to the technology's effectiveness. Key components of the circulation cell are its size, or radius of influence, and its percent capture or recirculation efficiency (Parsons 1999).

2.1.2 GCW System at CCAS

The GCW system installed at CCAS Facility 1381 is a 6-inch diameter polyvinyl chloride (PVC) well with two separate, wire-wrapped PVC well screens. The upper screened interval is 5 feet long and is installed from 5 to 10 feet below ground surface (bgs). The upper screened interval is a 20-slot (0.020-inch), wire-wrapped PVC screen. The lower screened interval is 10 feet long and was installed from a

TABLE A1. CHRONOLOGY OF GCW FIELD ACTIVITIES
Cape Canaveral Air Station, Cape Canaveral, Florida

DATE	DESCRIPTION OF FIELD EVENT
November 22-24, 1999	GCW drilled, installed and developed
January 28–February 25, 2000	Series of short term pumping tests performed in GCW to determine pumping and treatment system performance and operating parameters for long-term test
February 29, 2000	Begin long-term pump and treat test
April 3, 2000	End long-term pump and treat test
April 11-12, 2000	GCW run in circulation mode to test system operation
April 20, 2000	Begin long-term GCW test
June 26-28, 2000	Groundwater flow sensors installed
July 1, 2000	Groundwater flow sensor data collection begins
July 28, 2000	End long-term GCW test
August 1, 2000	Minitroll pressure transducers installed in 8 piezometers
August 2, 2000	Begin final pump-and-treat test
August 29,2000	End final pump-and-treat test
September 12, 2000	Pre-Test Activities 8:00 AM to 7:00 PM
September 13, 2000	Step drawdown tests performed in GCW: Step 1 - 10:30 AM to 11:30 AM Step 2 - 11:30 AM to 12:30 PM Step 3 - 12:30 PM to 3:00 PM Step 4 - 3:00 PM to 3:30 PM Recovery started at 3:30 PM
September 14, 2000	Dipole Flow Tests 1 through 5 conducted in GCW: Dipole Test 1 – 11:00 AM to 11:30 AM Dipole Test 2 – 12:00 PM to 12:30 PM Dipole Test 3 – 1:00 PM to 1:30 PM Dipole Test 4 – 2:00 PM to 2:30 PM Dipole Test 5 – 3:00 PM to 4:30 PM

TABLE 1. CHRONOLOGY OF GCW FIELD ACTIVITIES (continued)
Cape Canaveral Air Station, Cape Canaveral, Florida

DATE	DESCRIPTION OF FIELD ACTIVITY
September 15, 2000	Begin constant rate pumping test at 8:00 AM
September 16, 2000	End constant rate pumping test at 1:00 PM
September 18, 2000	End constant rate pumping test recovery period at 7:59 AM
September 18, 2000	Dipole Flow Tests 6 and 7 conducted in GCW: Dipole Test 6 – 8:00 AM to 10:22 AM Dipole Test 7 – 2:00 PM to 8:00 PM
September 19, 2000 to present	Continuous groundwater flow sensor data collection

depth of 20 to 30 feet below the ground surface. The lower screened interval is a 10-slot (0.010-inch), wire-wrapped PVC screen. A 5-foot sump was installed below the intake screen in the lower screened interval to act as a collection sump for sediments. Figure A3 is a schematic diagram of the GCW installation.

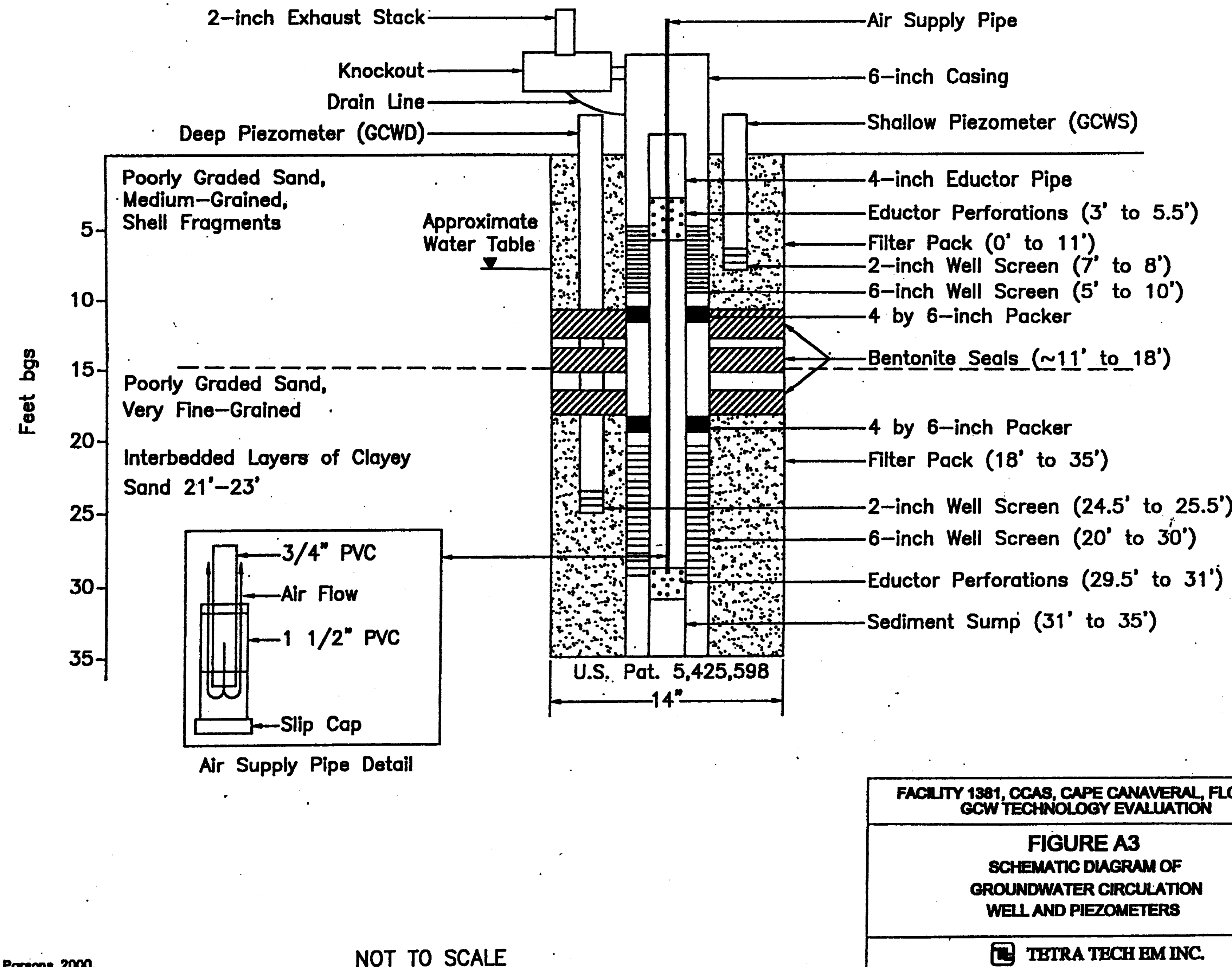
The boring drilled for installation of the GCW was 14 inches in diameter. Two piezometers were installed within the sand pack of the GCW boring, with the upper piezometer, GCWS, screened from 7 to 8 feet bgs, adjacent to the upper screened interval of the GCW. The lower piezometer, GCWD, was screened from 24.5 to 25.5 feet bgs, adjacent to the lower screened interval of the GCW.

Four piezometer pairs, each consisting of 1.5-inch diameter shallow and deep piezometers (2pzs/2pzd, 3pzs/3pzd, 4pzs/4pzd and 6pzs/6pzd), were installed within a 60-foot radius of the GCW. These piezometers, used as observation wells during the aquifer hydraulic testing, are screened from approximately 6 to 9.5 feet (shallow) and 22 to 26 feet (deep) bgs. Figure A4 shows the location of the GCW relative to the piezometers.

2.2 SITE LOCATION AND HISTORY

CCAS is situated on Canaveral Peninsula, a barrier island on the central Atlantic coast of Florida (Figure A1). Cape Canaveral is a headland, the easternmost point on Canaveral Peninsula. The city of Cape Canaveral lies just south of CCAS.

The main complex of CCAS consists of assembly and launch facilities for missiles and space vehicles and occupies approximately 25 square miles. The property is bounded by the Atlantic Ocean to the east and the Banana River to the west. The southern boundary is a manmade shipping canal, and the John F. Kennedy Space Center (KSC) adjoins CCAS to the north. Since its inception in 1950, CCAS has been a proving ground for research, development, and testing of the country's military missile programs. Seventy-three miles of paved roads at CCAS connect the various launch and support facilities with the centralized industrial area. The primary industrial activities at CCAS support missile launches from CCAS and spacecraft launches from KSC. Support for submarine port activities is also provided at CCAS (Parsons 1999).

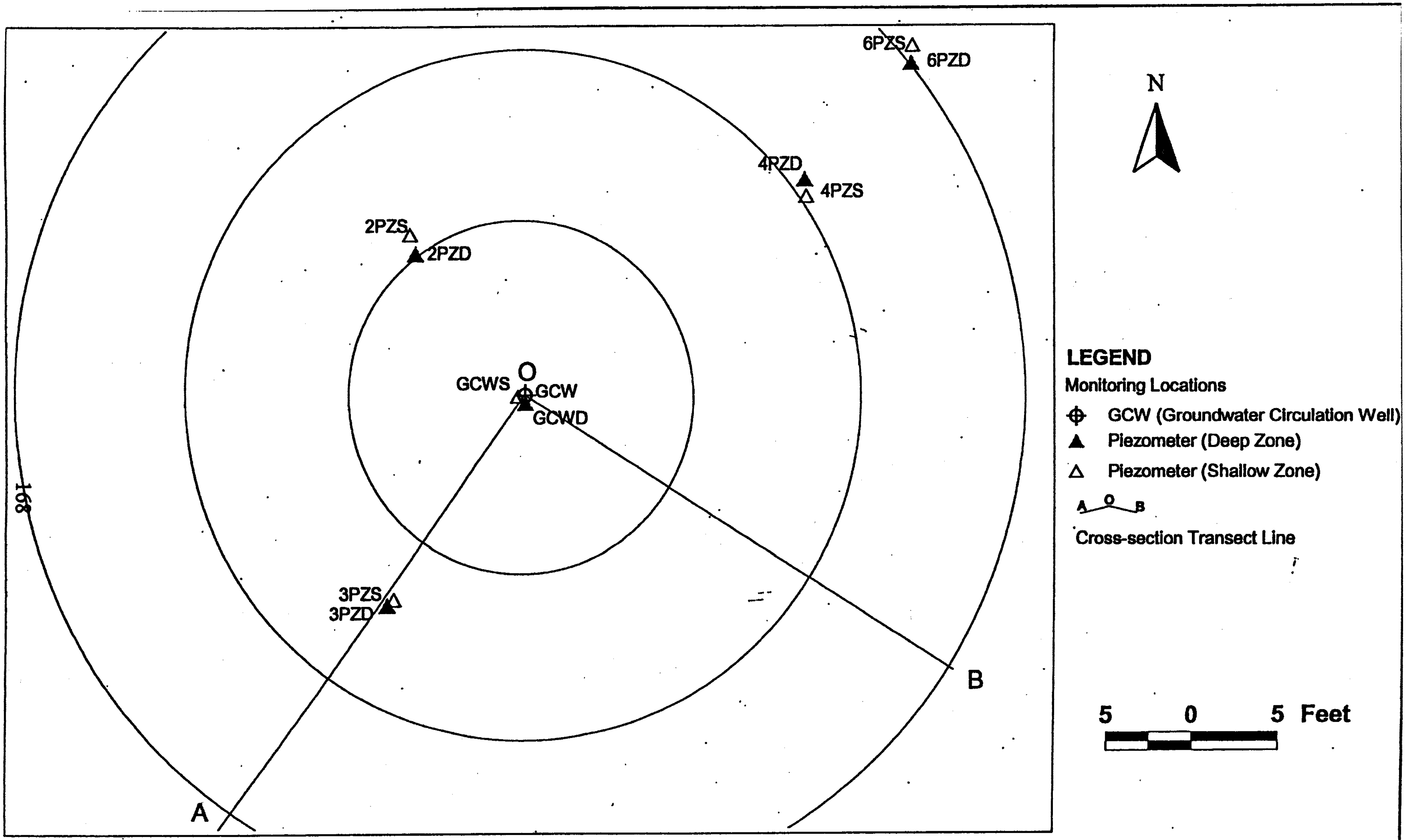


FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE A3
SCHEMATIC DIAGRAM OF GROUNDWATER CIRCULATION WELL AND PIEZOMETERS

TETRA TECH EM INC.

Source: Parsons 2000.



FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE A4
Locations of Groundwater Circulation Well and Piezometers

Tetra Tech EM Inc.

Facility 1381 is located in the central portion of CCAS (Figure A2) and has been used for several purposes since it was constructed in 1958. The building was used as the Guidance Azimuth Transfer Building for the 10 years that followed construction. Aerial photographs from the time indicate that numerous drums and tanker trucks were present at the facility. Verbal reports indicate that the tanker trucks were used to dump used waste solvents in the woods that surround the facility. In 1968, activity at the site was changed to an In-Place Precision Cleaning Laboratory. Specific activities included cleaning metal components in acid and solvent dip tanks, resulting in the generation of 3,300 gallons of waste trichloroethylene (TCE) per year. In 1977, the facility became the Ordnance Support Facility, and it has remained unchanged to the present (Parsons 1999).

2.3 SITE TOPOGRAPHY

CCAS is situated on Canaveral Peninsula, which is on the east side of Merritt Island, a barrier island in Brevard County on the Atlantic coast of Florida. Facility 1381 is located in the central portion of CCAS. The topography at Facility 1381 is relatively flat, with ground elevations ranging from approximately 5 to 8 feet above mean sea level (msl) (Parsons 1999). Vertical relief in the area is limited to drainage shoulders of canals that slope from the ground surface to the bed of the canal. Drainage canals are located 200 feet southwest (Landfill Canal) and 2,500 feet north (Northern Drainage Canal) of the GCW; both canals flow westward toward the Banana River. The system of drainage canals exerts a major influence on flow of shallow groundwater at Facility 1381.

2.4 REGIONAL AND SITE GEOLOGY

This section discusses the regional and site geology in the vicinity of CCAS and Facility 1381.

2.4.1 Regional Geology

Florida constitutes the southeast portion of the Atlantic Coastal Plain physiographic province of the southeastern United States. The Coastal Plain is a thick sequence of unconsolidated to semiconsolidated sedimentary rocks that range from Jurassic to Holocene in age. The configuration of rocks in the Coastal Plain is a tilted wedge that slopes and thickens seaward toward the Atlantic Ocean and the Gulf of Mexico.

In Florida, the sequence of sedimentary rocks that makes up the Coastal Plain is referred to as the Florida Platform. Rocks in the Florida Platform were deposited on top of an eroded surface of a crystalline rock complex, which is known collectively as the Florida basement rocks. The Florida basement rocks, consisting of low-grade metamorphics and igneous intrusives, occur several thousand feet below the land surface and are Precambrian, Paleozoic, and Mesozoic in age.

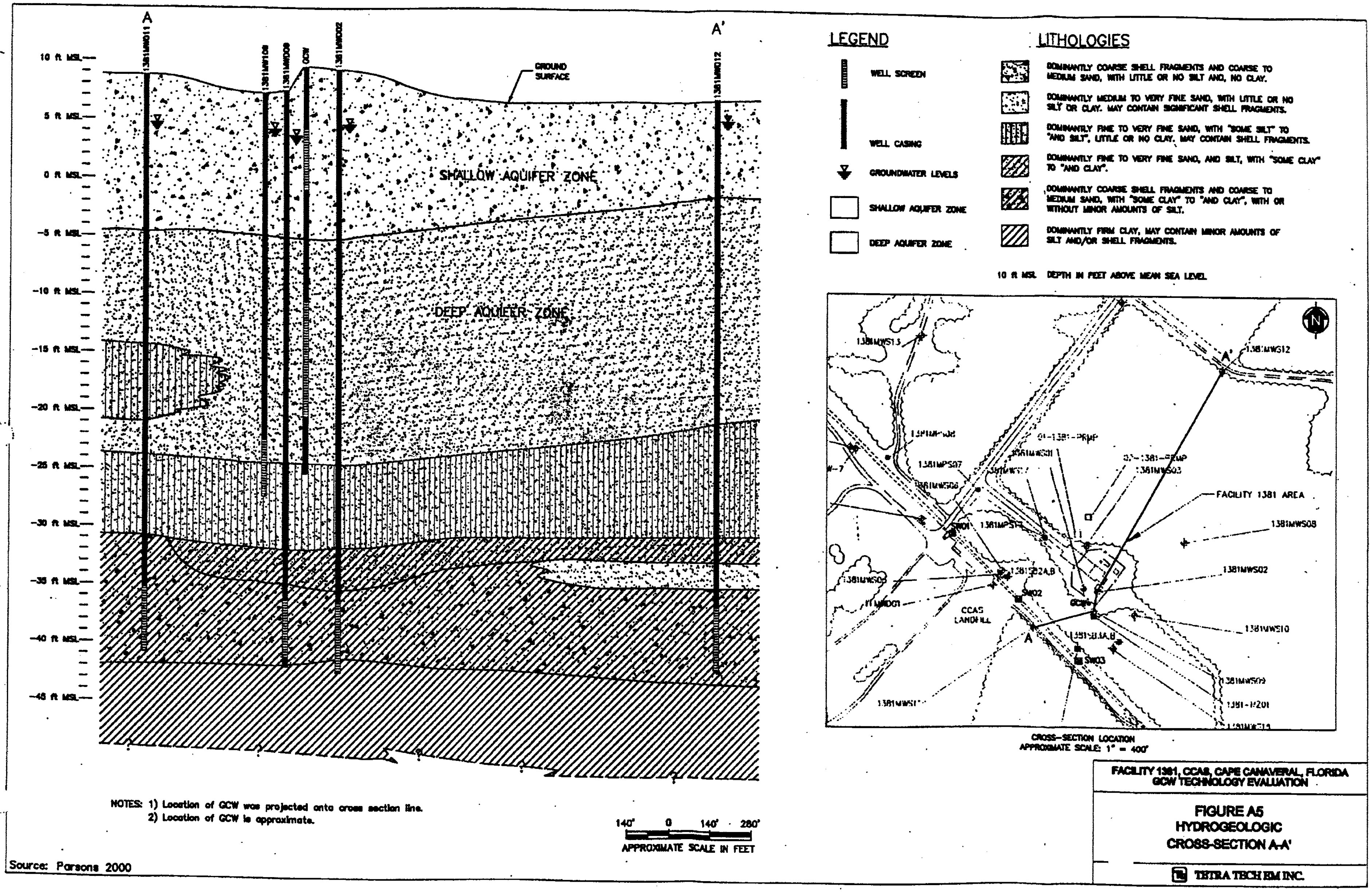
The base of the sedimentary rocks in the Florida Platform is made up of a thick, primarily carbonate sequence deposited from the Jurassic through the Paleocene. Starting in the Miocene and continuing through the Holocene, siliciclastic sedimentation became more dominant.

The east coast of Florida is bounded by a continental shelf that is moderately broad and slopes gently to the north but becomes both narrower and steeper to the south, toward Cape Canaveral. Cape Canaveral is a prominent feature, a large cuspate foreland or promontory that projects 13 miles seaward of the main coastal trend and strongly influences the orientation and sedimentation patterns along at least 80 miles of Florida's east coast. Cape Canaveral itself may have been formed by converging littoral transport along the coast (Davis 1997).

2.4.2 Site Geology

CCAS is situated on Canaveral Peninsula, which is on the east side of Merritt Island, a barrier island in Brevard County on the Atlantic coast of Florida. Facility 1381 is located in the central portion of CCAS. The topography at Facility 1381 is relatively flat, with ground elevations ranging from approximately 5 to 10 feet above msl (Parsons 2000). The topography consists of long, northeast-southwest trending low rises that are most likely depositional features associated with accretion of the barrier island. Vertical relief in the area is limited to shoulders of drainage canals that slope from the ground surface to the canal bed. Drainage canals are located 200 feet southwest (Landfill Canal) and 2,500 feet north (Northern Drainage Canal) of the GCW; both flow westward toward the Banana River.

The site geology is presented in cross-section A-A', which is shown as Figure A5. Based on previous work at the site conducted by Parsons (2000), the geology at Facility 1381 consists of unconsolidated sediments to a depth of at least 60 feet below ground surface. The upper 15 feet consists of poorly sorted, predominantly coarse shell material and coarse to medium sand.


A
A'
10 ft MSL
5 ft MSL
0 ft MSL
-5 ft MSL
-10 ft MSL
-15 ft MSL
-20 ft MSL
-25 ft MSL
-30 ft MSL
-35 ft MSL
-40 ft MSL
-45 ft MSL
GCW
GROUND SURFACE
SHALLOW AQUIFER ZONE
DEEP AQUIFER ZONE
LEGEND
WELL SCREEN
WELL CASING
GROUNDWATER LEVELS
SHALLOW AQUIFER ZONE
DEEP AQUIFER ZONE
LITHOLOGIES
DOMINANTLY COARSE SHELL FRAGMENTS AND COARSE TO MEDIUM SAND, WITH LITTLE OR NO SILT AND, NO CLAY.
DOMINANTLY MEDIUM TO VERY FINE SAND, WITH LITTLE OR NO SILT OR CLAY. MAY CONTAIN SIGNIFICANT SHELL FRAGMENTS.
DOMINANTLY FINE TO VERY FINE SAND, WITH "SOME SILT" TO "AND SILT", LITTLE OR NO CLAY. MAY CONTAIN SHELL FRAGMENTS.
DOMINANTLY FINE TO VERY FINE SAND, AND SILT, WITH "SOME CLAY" TO "AND CLAY".
DOMINANTLY COARSE SHELL FRAGMENTS AND COARSE TO MEDIUM SAND, WITH "SOME CLAY" TO "AND CLAY", WITH OR WITHOUT MINOR AMOUNTS OF SILT.
DOMINANTLY FIRM CLAY, MAY CONTAIN MINOR AMOUNTS OF SILT AND/OR SHELL FRAGMENTS.
10 ft MSL DEPTH IN FEET ABOVE MEAN SEA LEVEL
FACILITY 1381 AREA
CCAS LANDFILL
CROSS-SECTION LOCATION
APPROXIMATE SCALE: 1" = 400'
NOTES: 1) Location of GCW was projected onto cross section line.
2) Location of GCW is approximate.
140' 0 140' 280'
APPROXIMATE SCALE IN FEET
Source: Parsons 2000
FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION
FIGURE A5
HYDROGEOLOGIC
CROSS-SECTION A-A'
TETRA TECH EM INC.

The average grain size of the sand fraction decreases and the silt and clay content increases from depths of 35 feet to approximately 50 feet below ground surface. A 5-foot thick unit of fine to very fine-grained sand and silt occurs from 35 to 40 feet bgs. Shell fragments and coarse sand occur with varying amounts of clay from approximately 40 to 50 feet bgs. A layer of firm clay, which may be continuous across the site, has been encountered at a depth of 50 feet below the ground surface.

2.5 SITE HYDROGEOLOGY

The regional and site hydrogeology are discussed in the following two subsections.

2.5.1 Regional Hydrogeology

Regional hydrostratigrapic units that occur near Cape Canaveral are described below.

Surficial Aquifer. The uppermost water-bearing unit near the site is the surficial aquifer, which is unconfined and consists primarily of unconsolidated materials. The surficial aquifer system is a shallow, nonartesian aquifer, which occurs over much of eastern Florida but is not an important source of groundwater because better supplies are generally available from other aquifers.

The surficial aquifer system extends to a depth of approximately 50 to 60 feet bgs near CCAS. The surficial aquifer is described as consisting of fine to medium quartz sand that contains varying amounts of silt, clay, and loose shell fragments that are post-Miocene in age. In coastal areas, such as at CCAS, the surficial aquifer may also consist of partially cemented shell beds or coquina. The depth of the water table in the surficial aquifer ranges from at or near the land surface in low-lying areas to tens of feet below the land surface in areas of higher elevations.

The most important function of the surficial aquifer is to store water, some of which recharges the underlying Floridan aquifer. The surficial aquifer is little used as a source of drinking water because its permeability is low, resulting in relatively limited yield to wells, when compared with the Floridan aquifer system. The surficial aquifer is used for potable drinking water supplies only in coastal areas where the underlying Floridan aquifer may be brackish (Miller 1986).

The sands of the surficial aquifer generally grade into less permeable clayey or silty sands or low-permeability carbonate rocks at depths of usually less than 75 feet bgs. These rocks act as a confining unit for limestones that compose the underlying Floridan aquifer system. This upper confining unit of the Floridan aquifer system, as it is known, is generally composed of the middle Miocene-aged Hawthorn Formation, low-permeability rocks that in most places separate the Floridan aquifer from the surficial aquifer.

Floridan Aquifer. The Floridan aquifer system is a nearly vertically continuous, very thick sequence of generally highly permeable carbonate rocks. The degree of hydraulic connection of units that make up the Floridan aquifer depends primarily on the texture and mineralogy of the rocks that constitute the system (Miller 1986). The Floridan aquifer system is composed of sequences of limestone and dolomitic limestone.

The top of the Floridan Aquifer is defined as the first occurrence of vertically persistent, permeable, consolidated carbonate rocks. Rocks at the top of the Floridan aquifer at CCAS occur at an elevation of approximately 150.0 feet below mean sea level or at a depth of 160 feet bgs. The top unit of the Floridan aquifer at CCAS is composed of the Ocala Limestone of late Eocene age; the Floridan aquifer system ranges in thickness from 2,600 to 2,700 feet. The base of the Floridan aquifer system is defined as the first occurrence of anhydrite or presence of a gradational contact of generally permeable carbonate to much less permeable gypsiferous and anhydritic rocks. These low-permeability rocks, known as the lower confining unit of the Floridan aquifer system, everywhere underlie the Floridan. The transmissivity of the Upper Floridan aquifer that underlies CCAS is estimated to be 50,000 to 100,000 square feet per day (Miller 1986).

Geologic formations that make up the Floridan aquifer in east-central Florida are, from top to bottom, the Suwanee Limestone (where present), Eocene in age; the Ocala Limestone (where present); the Avon Park Formation; and, in some areas, all or part of the Oldsmar Formation. Paleocene rocks of the Cedar Keys Formation usually are recognized as forming the base of the Floridan aquifer system, except in areas where the upper part of the Cedar Keys Formation is permeable (Tibbals 1990).

2.5.2 Site Hydrogeology

The shallow aquifer zone at Facility 1381 is part of the surficial aquifer, which, as described previously, is a regionally unconfined water table aquifer. The water table at CCAS generally occurs at a depths ranging from 3 to 15 feet bgs. The water table occurred at approximately 8 feet bgs near the area where the groundwater circulation well was installed.

Flow of shallow groundwater at CCAS is controlled by an engineered drainage system consisting of a series of manmade canals, which were installed to reclaim land by lowering the water table. Surface water at the site drains through the canals and discharges into the Banana River, which is located west of CCAS. Closest to Facility 1381 is Landfill Canal, which is located 200 feet southwest; the Northern Drainage Canal is located about 2,500 feet due north of Facility 1381.

The canals strongly influence flow of shallow groundwater at the site. A groundwater divide is indicated near the GCW, as evidenced by groundwater flow to the southwest toward Landfill Canal, as well as to the northeast in the direction of the Northern Drainage Canal. Surface water elevations measured in the canals are lower than elevations of adjacent shallow groundwater, suggesting groundwater discharge to the canals (Parsons 2000).

The upper part of the surficial aquifer at Facility 1381 has been delineated into a shallow and a deep aquifer zone for this evaluation. The shallow aquifer zone is defined as the upper saturated portion of the aquifer, from the water table to the contact of the unit of coarse-grained shell and coarse to medium grained sand that occurs approximately 15 feet bgs. The shallow aquifer zone is approximately 8 feet thick. The deep aquifer zone is made up of medium to fine sand units, which occur at depths of 15 to 30 feet bgs. The shallow and deep aquifer zones are depicted on Figure A5, cross-section A-A'.

The hydraulic conductivity of the surficial aquifer at Facility 1381 was previously measured using rising head slug tests at a monitoring well pair, 1381MWS09 (screened 7.5 to 12.5 feet bgs) and 1381MWI09 (screened 30 to 35 feet bgs), located 55 feet southeast of the GCW. The calculated hydraulic conductivity values are 11.6 feet per day for the shallow well and 0.4 feet per day for the deep well.

Slug testing by Parsons in piezometers near the GCW yielded hydraulic conductivity values of 17.8 to 24.2 feet per day in piezometer 4PZS (screened 6.5 to 9.5 feet bgs) in the shallow aquifer zone and 0.1 to 0.2 feet per day in piezometers 2PZD (screened 21.3 to 24.6 feet bgs) and 6PZD (screened 22.7 to 26 feet bgs) in the deep aquifer zone. The groundwater velocity in the shallow aquifer zone under natural flow conditions is estimated at 0.21 feet per day (Parsons 2000).

Based on the pumping test data, the hydraulic conductivity of the estimated saturated portion of the aquifer (42 feet thick) ranges from 43 to 53 feet per day.

2.6 CONTAMINATION IN SOIL AND GROUNDWATER

Contamination in soil and groundwater at Facility 1381 is attributable to historical waste disposal practices. A plume of contaminants in groundwater, consisting primarily of TCE and associated degradation products including cis-1,2-dichloroethene (cis-1,2-DCE) and vinyl chloride, has been detected at the site. The plume is 110 acres in areal extent and is 2,500 feet long. The axis of the plume is elongated to the north-northeast.

The maximum concentration of TCE detected to date in the suspected source area is 342,000 micrograms per liter (μg/L) (Parsons 2000). Concentrations of TCE measured in samples from the source area have been lower during more recent sampling rounds.

2.7 SITE HYDROGEOLOGICAL CONCEPTUAL MODEL

The site hydrogeological conceptual model for the tested aquifer that underlies CCAS Facility 1381, where the GCW is installed, is described below.

- The uppermost hydrostratigraphic unit that underlies Facility 1381 is part of the surficial aquifer system of Florida, a water table aquifer that consists of Quaternary-aged sediments.
- The aquifer tested at Facility 1381 is approximately 42 feet thick.
- The upper 10 feet of the aquifer tested (to a depth of approximately 15 bgs), designated at the shallow aquifer zone, consists of poorly sorted, coarse to medium sand with little or no silt and no clay; coarse-grained shell fragments occur mostly as lenses in the sand.
- The lower portion of the aquifer tested (15 to 40 feet bgs), designated as the deep aquifer zone, consists of medium to fine sand with shell fragments; the grain size of the sand decreases further to very fine, with percentages of silt and clay increasing from 35 to 40 feet bgs.
- At a depth of about 50 feet bgs, a 10-foot thick layer of firm clay that contains minor amounts of silt is interpreted as continuous across the site.
- In general, the aquifer tested is heterogeneous and anisotropic. Horizontal hydraulic conductivities of the various aquifer zones change with depth. Horizontal hydraulic conductivities decrease with depth near the GCW.
- The shallow aquifer zone is more permeable than the deep aquifer zone. The hydraulic conductivity of the shallow aquifer zone is estimated to be approximately 20 feet per day; the hydraulic conductivity of the deep aquifer zone is estimated to be approximately 0.2 feet per day.

- The static water table occurs at a depth of 8 feet bgs in the area where the groundwater circulation well was installed.

- Groundwater in the aquifer tested is likely influenced by the manmade drainage canals. The canals discharge into the Banana River west of CCAS.

- Measurements of groundwater elevation indicate that a groundwater divide may exist at Facility 1381 as a result of effects of the two canals; groundwater southwest of the divide flows toward the Landfill Canal, and groundwater northeast of the divide flows toward the Northern Drainage Canal.

- The canals can behave as either lateral sources of recharge to the aquifer or may receive lateral discharge from the aquifer when recharge by vertical infiltration is significant.

- The static water table at the site is very flat, possibly because of the low topographic relief at or near the groundwater divide. A dominant direction of groundwater flow under natural conditions cannot be identified.

3.0 AQUIFER TESTING

Aquifer hydraulic testing was conducted to obtain information that could be used to assess the degree of hydraulic communication among various portions of the aquifer beneath the site, as well as to estimate hydraulic parameters of the aquifer, such as hydraulic conductivity, transmissivity, storativity, and anisotropy. In addition, the aquifer tests provided data that could be used to calculate well efficiencies of the two screened intervals of the GCW.

The aquifer hydraulic testing was conducted using the lower screened interval of the GCW as the pumping well. An inflatable packer was used to isolate the two screened intervals of the GCW to facilitate pumping from only the lower screened interval. Piezometer pairs installed in both the upper and lower portions of the aquifer were used as observation wells during the aquifer tests.

Aquifer hydraulic tests using the GCW were conducted to estimate or assess the following:

- Hydraulic parameters of the upper and lower portions of the aquifer, including estimation of hydraulic conductivity, transmissivity, storativity, and anisotropy.
- The radius of influence established during pumping.
- Evidence of barriers that may affect hydraulic communication between the upper and lower zones of the aquifer.

Aquifer hydraulic testing consisted of step tests, a constant rate pumping test, and dipole tests, which are discussed later in this appendix.

The next section describes the aquifer testing equipment and the aquifer testing methodologies.

3.1 AQUIFER TESTING EQUIPMENT

This section discusses the equipment used during the aquifer testing.

3.1.1 Installation and Configuration of Aquifer Test Equipment

Aquifer tests were conducted using the lower screened interval of the GCW and consisted of a step drawdown test, a constant discharge pumping test, and dipole flow tests. This section describes installation and configuration of aquifer testing equipment.

3.1.1.1 Pump and Packer Equipment

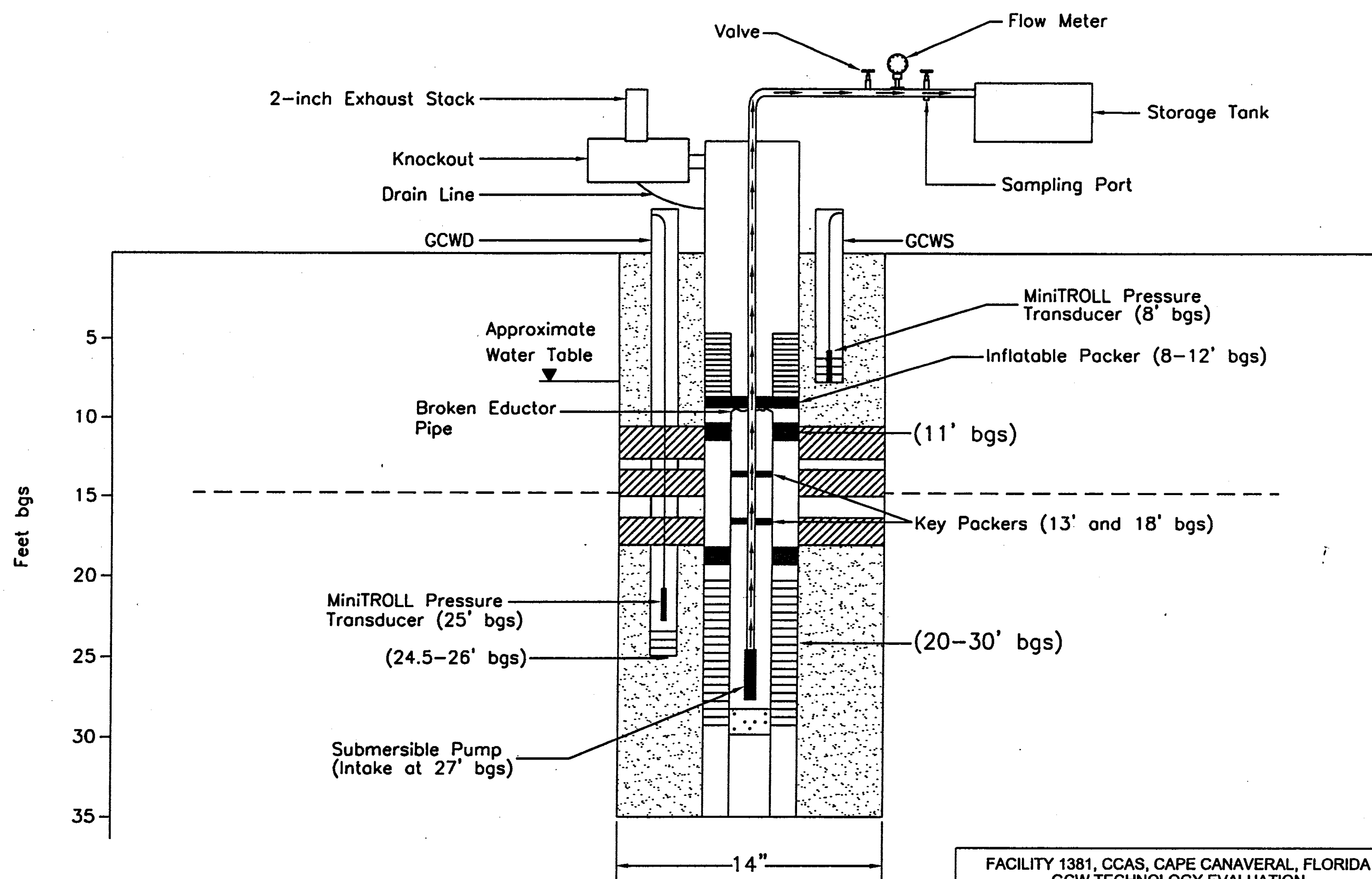
The configuration of the pump and packer equipment was identical for the step drawdown test and constant discharge pumping test conducted in the lower screened interval of the GCW, shown schematically in Figure A6. The two screened intervals were hydraulically separated using a 5-inch-diameter, 5-foot-long inflatable multiple key packer to pump only from the lower screened interval of the GCW well. The inflatable key packer was inserted between the two screened intervals at a depth of approximately 13 to 18 feet bgs. The pump used for the aquifer testing was a 4-inch stainless steel Grundfos submersible pump with a maximum capacity of 100 gallons per minute. The pump was installed below the packer with the intake at approximately 27 feet bgs. The assembly for the pump and packer was set in the GCW using a 2-inch diameter, steel drop pipe (Figure A6). The drop pipe was secured at the wellhead and connected to a 2-inch diameter PVC discharge line. After the pump was set, the packer was inflated using a pressurized nitrogen cylinder. The packer's pressure was monitored throughout the pumping tests at the wellhead using a pressure gauge.

The same equipment was used for the dipole flow tests. The setup for the dipole flow test is shown schematically in Figure A7. The packer was installed at approximately 13 to 18 feet bgs, and the submersible pump was set immediately below the packer at approximately 27 feet bgs.

3.1.1.2 Pressure Transducers and Data Loggers

MiniTROLL pressure transducers manufactured by InSitu of Laramie, Wyoming, were installed in the piezometers. The miniTROLL is an integrated silicon strain-gauge pressure sensor. The instrument is 0.72 inches in diameter and contains internal pressure and temperature sensors. Pressure readings are automatically adjusted for fluctuations in barometric pressure and temperature.

During installation of the transducer, the depth to groundwater was measured with an electronic water level sounder before the transducer was lowered into the well. The miniTROLL transducer was set at a depth so that it would remain submerged during the pumping test at a depth below water that would not exceed the pressure rating of the transducer. The cable for the pressure transducer was secured to the



FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE A6
SCHEMATIC DIAGRAM OF CONSTANT RATE PUMPING TEST SET-UP

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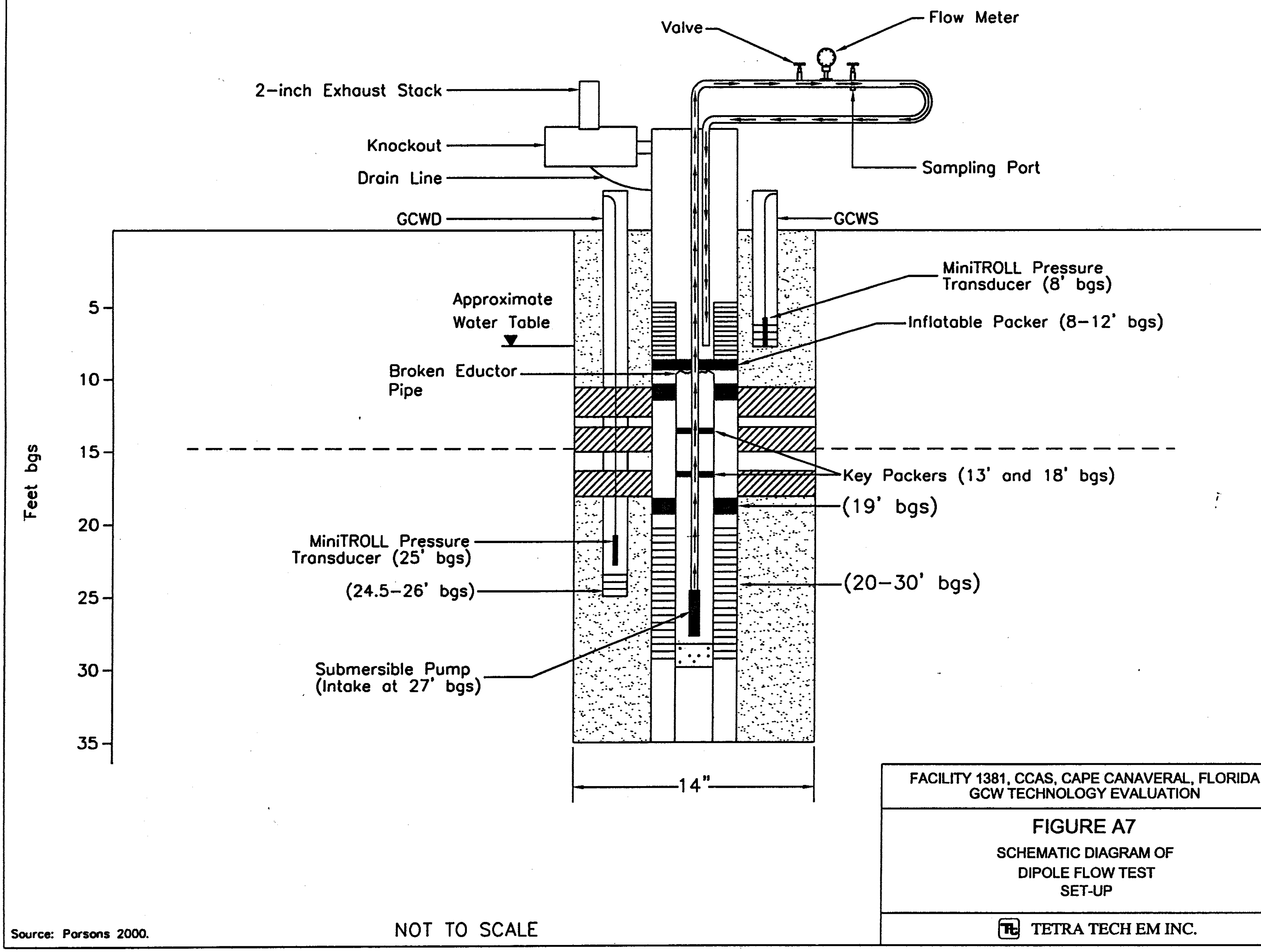
Source: Parsons 2000.

NOT TO SCALE



Source: Parsons 2000.

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FIGURE A7
SCHEMATIC DIAGRAM OF DIPOLE FLOW TEST SET-UP

TETRA TECH EM INC.

wellhead at the surface using duct tape, so that no movement occurred during aquifer testing. A reading of the length of the column of water above the transducer was recorded after the transducer was secured.

Data from the miniTROLL installed in each of the piezometers were periodically downloaded to a laptop computer during aquifer testing to view data recorded. In addition, data from the transducers were periodically checked by collecting water level measurements using an electronic water level sounder.

3.1.1.3 Other Equipment

The pumping and injection rates were regulated during the aquifer tests using a variable rate controller, a flow control valve, and two inline flow meters. The flow meters used were a McCrometer electronic flow meter with totalizer and a Precision flow meter with totalizer. The meters were installed on the discharge pipe at the wellhead. The flow meters were calibrated in the field by measuring the time required to fill a 5-gallon bucket with water pumped through the discharge line.

All water generated during the pumping tests was piped to on-site storage tanks to await chemical characterization and subsequent disposal. A 21,000-gallon tank was staged on site for storage of the extracted groundwater to accommodate the volume of water generated during the pumping test. Water quality parameters including pH, oxidation and reduction potential, specific conductance, temperature, and dissolved oxygen were measured during development and removal of the well water. Horiba U10 and YSI 2000 water quality meters were used to measure the water quality parameters in the field. The instruments were calibrated daily in accordance with the manufacturer's instructions.

3.1.1.4 Data Logger Programming

The miniTROLLtroll data loggers were programmed using the length of the column of water above the transducer, depth of water below the top of well casing, and the survey elevation on the top of the casing so that subsequent readings were relative to the groundwater elevation. The data loggers were programmed for each aquifer test to collect data at specific times and frequencies. Because of significant responses in water level to changes in pumping rate (including starting and stopping pumping), the data loggers for the GCW piezometers and the other observation wells were programmed to collect data at a higher frequency immediately after any change in pumping rate.

The programmed data collection schedule was as follows: every half-second for 20 readings, every second for 50 readings, every 2 seconds for 60 readings, every 5 seconds for 60 readings, every 10 seconds for 30 readings, every minute for 20 readings, every 2 minutes for 20 readings, every 5 minutes for 12 readings, every 10 minutes for 18 readings, and every 20 minutes for 500 readings. (This schedule was reinitiated after any change in pumping rate and was generally terminated before the last step was complete.) Collecting water level measurements in this manner provided data at higher frequencies when the rate of change in water level was greater. Data loggers for the observation wells were programmed to collect data at lower frequencies, typically once per minute. All data were downloaded from the data logger to a computer, and the data logger was reset between each aquifer test.

3.2 METHODOLOGY FOR AQUIFER TESTING

This section describes the methodologies used for each of the aquifer testing events.

3.2.1 Step Drawdown Test

Tetra Tech conducted a step drawdown test in the lower screened interval of the GCW to estimate the optimal pumping rate for a constant discharge pumping test, and to estimate the specific capacity and the well efficiency of the lower screened interval of the GCW. Test procedures and results are discussed below.

A step drawdown test was conducted on September 13, 2000, using the lower screened section of the GCW. The objectives of the step drawdown test were to assess the optimal pumping rate for the constant rate pumping test and to evaluate the specific capacity and well efficiency of the lower screened interval of the GCW. Table A2 summarizes events recorded during the step tests

The step drawdown test was conducted by isolating the upper and lower screened sections of the GCW using a packer system and pumping from the lower screened section of the well. The step drawdown test was conducted by pumping at successive rates of 1.9, 5.9, 12.5, and 15 gallons per minute (gpm). The first (1.9 gpm) and second (5.9 gpm) pumping steps were operated for 1 hour each. The third step (12.5 gpm) was conducted for about 2.5 hours. During the fourth step (15 gpm), the drawdown in the well reached the pump intake level after about 30 minutes of pumping. At that time, the pump began to produce a mixture of air and water and pumping was terminated.

TABLE A2

TEST EXECUTION SUMMARY, STEP DRAWDOWN TEST
Cape Canaveral Air Station, Cape Canaveral, Florida

Step	Pumping Rate	Date/Time (Duration)	Comments
1	1.9 gpm	(9/13/00) 1030 to 1130	No flow meter was available. Difficult to control flow rate with a large ball valve. Pumping rate was calculated from totalizer reading. Flow rate was adjusted at the beginning of the step.
2	5.9 gpm	(9/13/00) 1130 to 1230	Increase flow rate at 1130. Difficult to control flow rate. The flow rate was as high as 15 gpm during the two-minute period at beginning.
3	12.5 gpm	(9/13/00) 1230 to 1500	Pumping rate was well adjusted without fluctuation. Pumping step was conducted longer because water level in GCWD did not appear to be stabilized during the step.
4	about 15 gpm	(9/13/00) 1500 to 1530	Test the maximum yield capacity of the lower screen of the GCW. Pump started pumping air several minute after the pumping step started.
Recovery	0 gpm	(9/13/00) Started 1530	Pump shut off; monitor aquifer recovery

Groundwater levels were monitored during the step tests at piezometers GCWD, GCWS, 2pzd, 2pzs, 3pzd, 3pzs, 4pzd, and 4pzs during the step drawdown test. Piezometers GCWD and GCWS are installed within the sand pack of the GCW. Figure A8 is a hydrograph of water levels recorded in piezometers GCWS and GCWD during the aquifer testing events. Figure A9 is a hydrograph of water levels recorded in piezometers GCWS and GCWD during the step tests. It is possible that due to the placement of the screened interval with relation to the water table, piezometer GCWS went dry during a portion of the aquifer testing events.

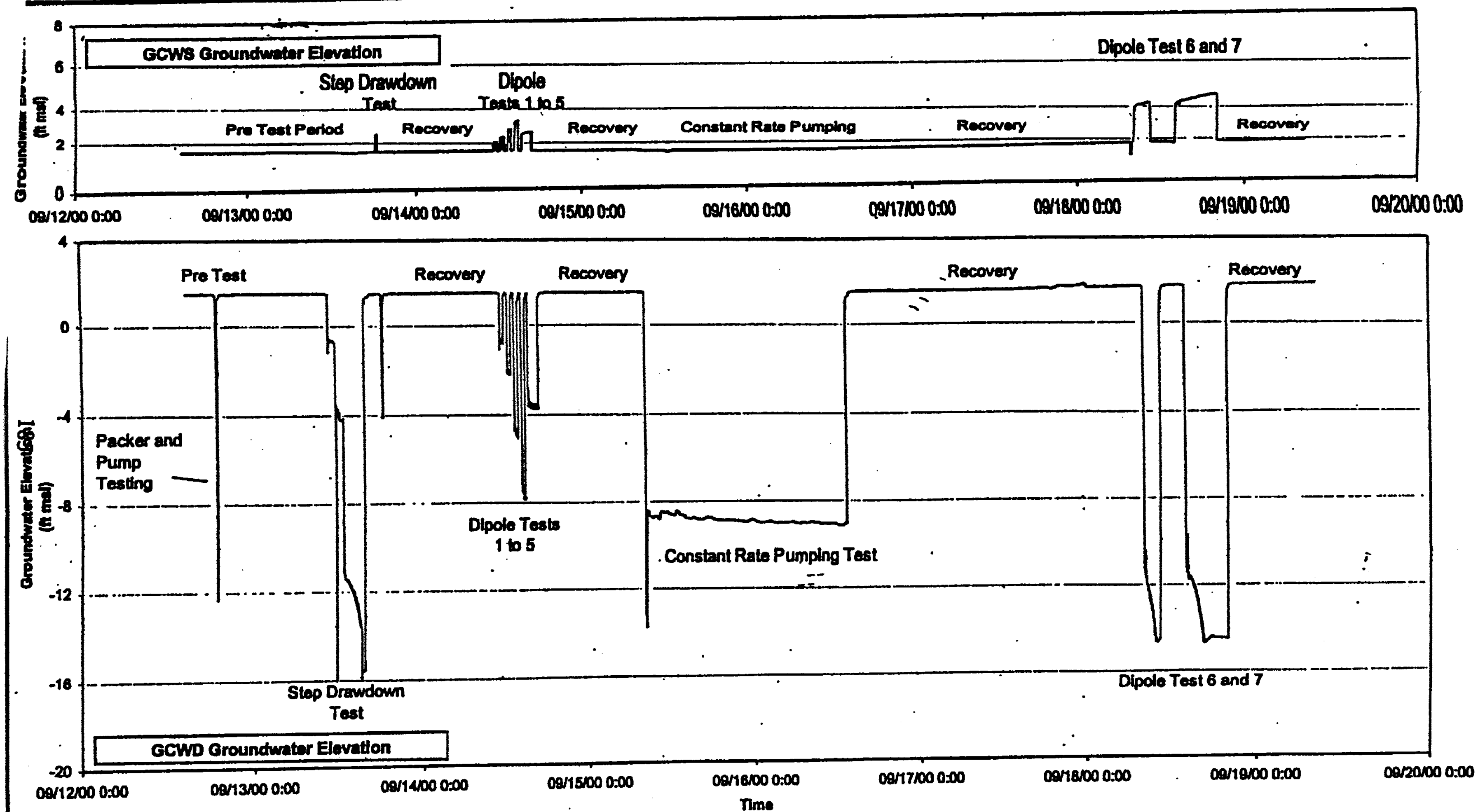
3.2.2 Constant Discharge Pumping Test

A constant rate pumping test was conducted on September 15, 2000, using the lower screened portion of the GCW. The objective of the constant rate pumping test was to quantify the hydraulic characteristics of the aquifer, specifically hydraulic conductivity, transmissivity, storativity, and anisotropy of the deep aquifer zone.

The constant rate pumping test was conducted by first isolating the upper and lower screened sections of the GCW using inflatable multiple key packers. Water was pumped from the lower screened interval of the GCW at a constant rate of approximately 10 gpm for 29 hours. Water levels in piezometers GCWD, GCWS, 2pzs, 2pzd, 3pzs, 3pzd, 4pzs, 4pzd and 6pzd were monitored during the test using pressure transducers and data loggers. Figure A10 is a hydrograph of water levels recorded in piezometers GCWS and GCWD during the constant rate pumping test. Table A3 is a summary of the constant discharge pumping test.

Water level recovery data were collected in the piezometers after the pumping was stopped. The recovery period lasted approximately 43 hours.

A constant discharge pumping test in the upper screened interval was conducted after the step drawdown test in the upper screened interval of the GCW well and after the water level in the pumping well, the observation piezometer, and the observation wells had recovered complete. Procedures and results for the constant discharge pumping test are discussed in Section 4.0.



NOTE: Aquifer test period was September 12 to 19, 2000.

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GCW TECHNOLOGY EVALUATION

FIGURE A8
Hydrograph of GCWS and GCWD During Aquifer Hydraulic Testing

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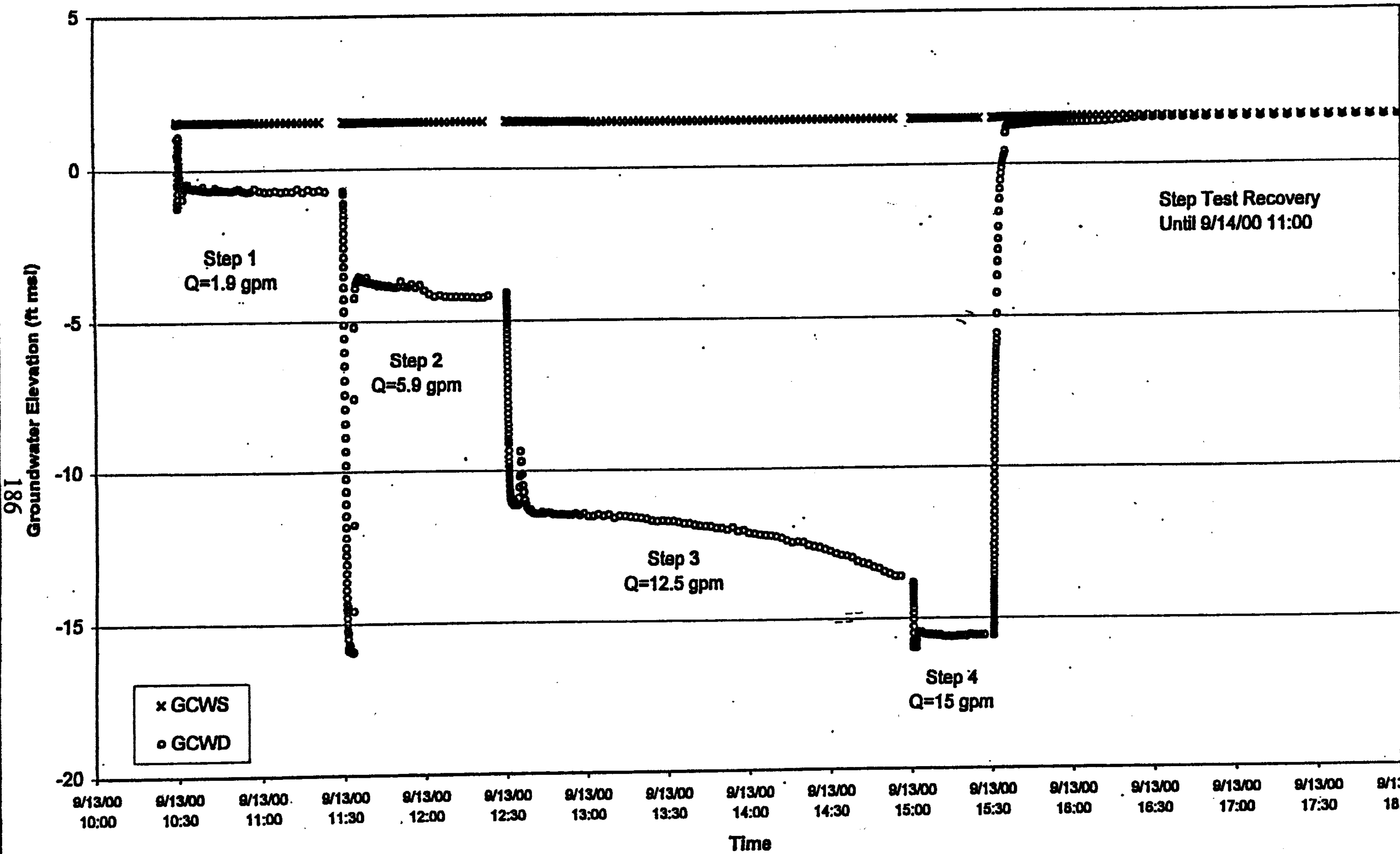

NOTE: Data shown is from step tests conducted on 9/13/00.

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GCW TECHNOLOGY EVALUATION

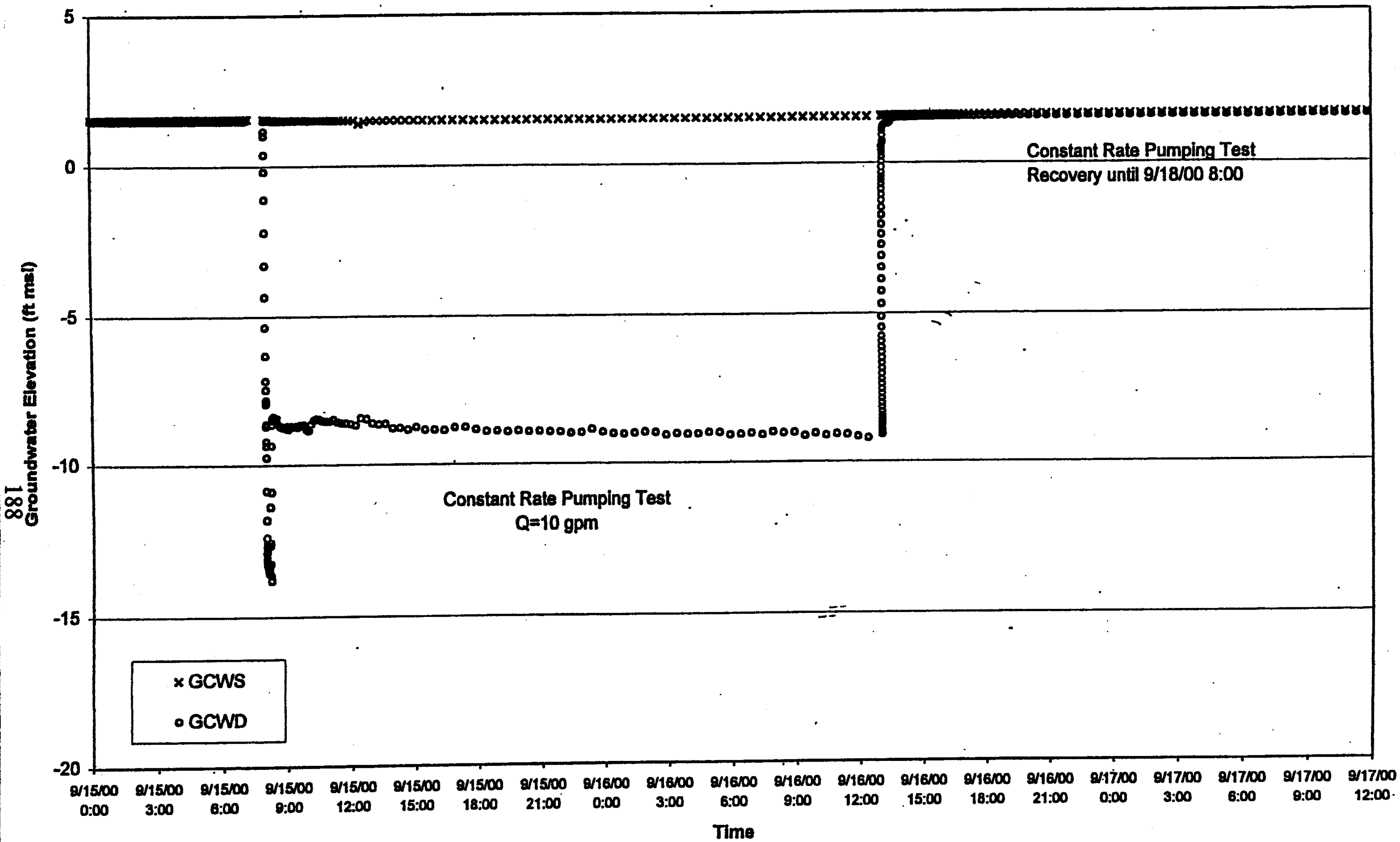
FIGURE A9
Hydrograph of GCWS and GCWD During Step Drawdown Tests

Tetra Tech EM Inc.

TABLE A3

TEST EXECUTION SUMMARY, CONSTANT DISCHARGE PUMPING TEST
Cape Canaveral Air Station, Cape Canaveral, Florida

Step	Pumping Rate	Date/Time	Comments
0	0 gpm	(9/15/00) 0732	Static groundwater level at 10.84 feet below top of casing in GCWS.
1	10 gpm	(9/15/00) 0800 (9/15) to 1300 (9/16)	Begin constant rate pumping test.
Recovery	0 gpm	(9/15/00) 1300 (9/16) to 0800 (9/18)	Pump shut off; monitor aquifer recovery



NOTE: Data shown is from constant rate test conducted from 9/15/00 to 9/16/00.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE A10
Hydrograph of GCWS and GCWD Under Pumping Conditions

Tetra Tech EM Inc.

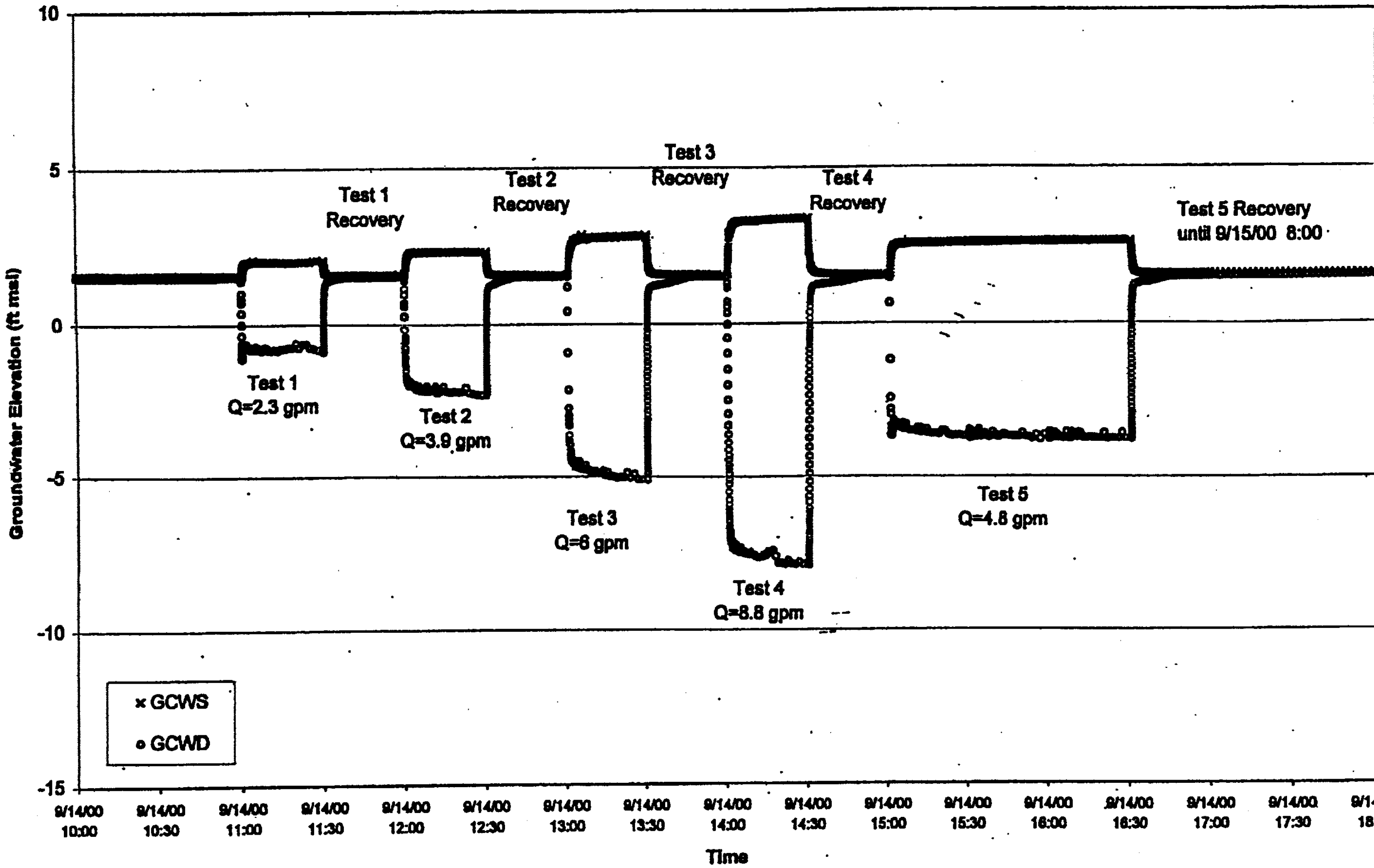
3.2.3 Dipole Flow Testing

Tetra Tech conducted multiple dipole tests using the GCW on September 14 and 18, 2000. The dipole tests were conducted by simultaneously pumping from the lower interval screened in the deep aquifer zone and injecting the pumped groundwater into the upper interval screened in the shallow aquifer zone. The pumping rate was equal to the injection rate in each of the dipole tests. Water levels in piezometers GCWD and GCWS, 2pzd, 2pzs, 3pzd, 3pzs, 4pzd, 4pzs and 6pzd were monitored using pressure transducers and data loggers in each of the dipole tests.

Five separate tests were conducted with different pumping and injection rates during the dipole flow tests conducted on September 14. These tests were designated Dipole Tests 1 through 5.

Groundwater was pumped and injected simultaneously at rates of 2.3, 3.7, 6.0, 8.8, and 4.8 gpm; each test lasted 30 minutes, except for the final test, which lasted 90 minutes. A recovery period of 30 minutes occurred between each test. Since relatively fast recoveries in water level were observed in the lower and upper screened intervals of the GCW during the step drawdown tests, a 30-minute recovery period after each dipole test was considered adequate. The adequacy of the recovery period is verified by Figure A11, which is a hydrograph of water levels in piezometers GCWS and GCWD recorded during Dipole Tests 1 through 5.

An additional dipole flow test was conducted on September 18 using a higher flow rate and a longer test period, specifically pumping and injecting groundwater at a rate of 12.5 gpm for 8 to 10 hours. However, 82 minutes into the test, pumping was inadvertently stopped because of a power failure and early logarithmic data for the water level recovery could not be collected. This test was designated Dipole Test 6. Later on September 18, a second dipole flow test (designated Dipole Test 7) was conducted, also with a pumping and injection rate of 12.5 gpm, for 360 minutes. Figure A12 is a hydrograph of water levels recorded in piezometers GCWS and GCWD during Dipole Tests 6 and 7. Table A4 is a summary of the dipole flow test.



NOTE: Data shown is from Dipole tests 1 through 5 conducted from 9/14/00 to 9/15/00.

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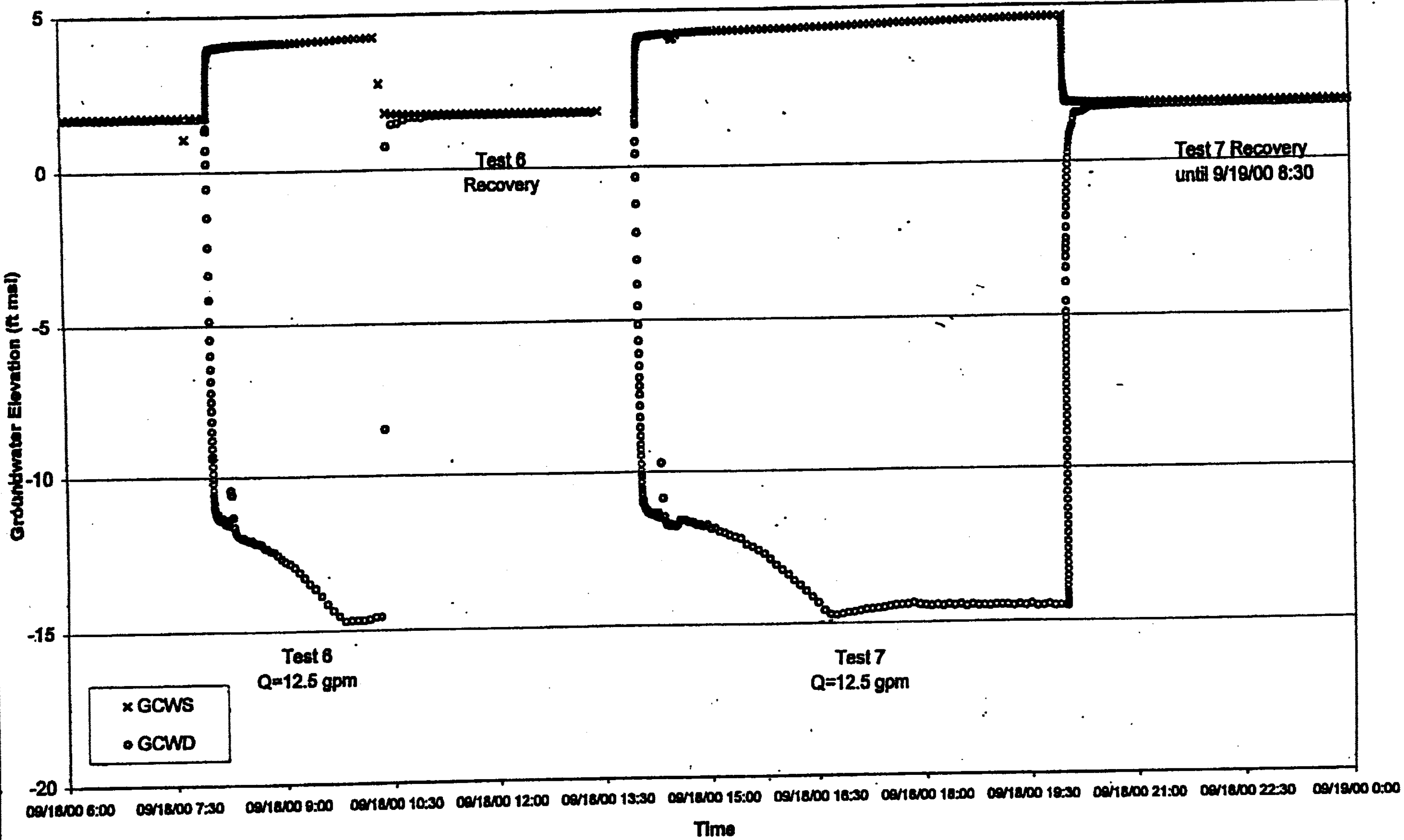
GCW TECHNOLOGY EVALUATION

FIGURE A11
Hydrograph of GCWS and GCWD During Dipole Tests 1 through 5

Tetra Tech EM Inc.



NOTE: Data shown is from Dipole tests 6 and 7 conducted on 9/18/00.

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GCW TECHNOLOGY EVALUATION

FIGURE A12
Hydrograph of GCWS and GCWD
During Dipole Tests 6 and 7

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TABLE A4
TEST EXECUTION SUMMARY, DIPOLE FLOW TESTS
Cape Canaveral Air Station, Cape Canaveral, Florida

Test Number	Pumping/Injection Rate (gpm)	Time	Comments
DFT on September 14, 2000			
0	0	(9/14) 08:46	Static groundwater level below top of casing at 10.85 feet in GCWS and 8.85 feet in GCWD.
1	2.3	11:00 to 11:30	Water level increased about 0.498 feet from static water level in GCWS. Water level decreased about 2.33 feet from static water level in GCWD.
Test 1 Recovery	0	11:30 to 12:00	Test 1 recovery period. Water levels in GCWD and GCWS were fully recovered. Recovered static water level was 0.025 feet higher in GCWS and 0.005 feet lower in GCWD in comparison with the original static water levels.
2	3.7	12:00 to 12:30	Water level increased about 0.733 feet from recovered static water level in GCWS. Water level decreased about 3.79 feet from recovered static water level in GCWD.
Test 2 Recovery	0	12:30 to 13:00	Test 2 recovery period. Water levels in GCWD and GCWS were fully recovered. Recovered static water was 0.004 feet higher in GCWS and identical to static in GCWD in comparison with the original static water levels.
3	6	13:00 to 13:30	Water level increased about 1.28 feet in GCWS. Water level decreased about 6.59 feet in GCWD.
Test 3 Recovery	0	13:30 to 14:00	Test 3 recovery period. Water levels in GCWD and GCWS were fully recovered. Recovered static water was 0.002 feet higher in GCWS and GCWS and 0.007 feet lower in GCWD in comparison with the original static water levels.
4	8.8	14:00 to 14:30	Water level increased about 1.8 feet in GCWS. Water level decreased about 9.4 feet in GCWD.
Test 4 Recovery	0	14:30 to 15:00	Test 4 recovery period. Water levels in GCWD and GCWS were fully recovered. Recovered static water levels were 0.004 feet higher in GCWS and 0.002 feet higher in GCWD in comparison with the original static water levels.
5	4.8	15:00 to 16:30	Water level increased about 1.07 feet from the static water level in GCWS. Water level decreased about 5.28 feet from the static water level in GCWD.
Test 5 Recovery	0	16:30 to 07:00 (9/15/00)	Test 5 recovery period. Water levels in GCWD and GCWS were fully recovered. Static water levels were 0.016 feet higher in GCWS and 0.023 feet higher in GCWD at the end of the recovery period.
DFT on September 18, 2000			
	0	9/18 07:30	Static groundwater level below top of casing at 10.66 feet in GCWS and 8.67 feet in GCWD.
6	12.5	8:00 to 10:22	Water level increased about 2.51 feet from static water level in GCWS. Water level decreased about 16.25 feet from static water level in GCWD.
Test 6 Recovery	0	10:22 to 14:00	Test 6 recovery period. Water levels in GCWD and GCWS were fully recovered. Recovered static water levels were 0.072 feet higher in GCWS and 0.044 feet higher in GCWD in comparison with the original static water levels.
7	12.5	14:00 to 20:00	Water level increased about 2.96 feet from recovered static water level in GCWS. Water level decreased about 16.27 feet from recovered static water level in GCWD.
Test 7 Recovery	0	20:00 to 08:24 (9/19)	Test 7 recovery period water levels in GCWD and GCWS were fully recovered. Recovered water levels were 0.133 feet higher in GCWS and 0.122 feet higher in GCWD.

4.0 RESULTS AND INTERPRETATION OF AQUIFER TESTING

This section interprets and discusses the data collected during the aquifer hydraulic tests, and provides calculations of well-specific yield and efficiency and of hydraulic parameters in the aquifer.

4.1 CALCULATION OF SPECIFIC CAPACITY AND WELL EFFICIENCY

This section presents the calculations of specific capacity and well efficiency for the GCW. The calculations are based on water level data collected from the step-drawdown test conducted in the upper screened portion of the well (screened in the upper aquifer zone), the step-drawdown conducted in the lower screened portion (screened in the deep aquifer zone), and the water injection test conducted in the upper screened portion of the GCW.

4.1.1 Specific Capacity

The specific capacity of a pumping well is calculated based on (1) the pumping rate and measured maximum drawdown during various steps of the step drawdown test, or (2) the injection rate and maximum rise in water level for injection tests (assuming the drawdown and rise in water level have stabilized) during an injection (dipole) test. The step drawdown test in the lower screened interval (deep aquifer zone) was conducted in four steps. The upper screened interval (shallow aquifer zone) injection (dipole) testing was conducted in seven steps.

Figures A8 and A9 show water levels in piezometers GCWS and GCWD recorded during the step drawdown test. Table A5 shows the data for the step and dipole tests and the specific capacities calculated from each of the tests. Based on the response in the lower screened interval during the aquifer step drawdown test, the specific capacity of the GCW calculated for various steps ranges from 0.83 to 1.03 gpm per foot, with an average of 0.89 gpm per foot. Based on the results of the dipole tests, the specific capacity of the lower screened interval ranges from 0.77 to 1.03 gallons per minute per foot (gpm/ft), with an average of 0.90 gpm/ft, virtually the same as the average obtained from the step drawdown test results. The aquifer injection (dipole) test resulted in calculated specific capacities for the shallow aquifer zone ranging from 4.18 to 5.09 gpm/ft, with an average of 4.50 gpm/ft. The higher specific capacity of the shallow aquifer zone indicates that it is more permeable or transmissive than the deep aquifer zone.

TABLE A5. AQUIFER TEST DATA AND GROUNDWATER CIRCULATION WELL SPECIFIC CAPACITY
Cape Canaveral Air Station, Cape Canaveral, Florida

Test	Test Step	Pumping or Recharge Rate (Q) (gpm)	Measured Maximum Drawdown or Water Level Rise (s) (feet)	Specific Capacity[a] (gpm/foot)	Average Specific Capacity (gpm/foot)
Lower Screen Step Drawdown Test	1	1.9	2.24	0.85	0.89
	2	5.9	5.75	1.03	
	3	12.5	15.10	0.83	
	4	15.0	17.11	0.88	
Lower Screen Dipole Test (Pumping)	1	2.3	2.39	0.96	0.90
	2	3.9	3.78	1.03	
	3	6.0	6.60	0.91	
	4	8.8	9.34	0.94	
	5	4.8	5.24	0.92	
	6	12.5	16.19	0.77	
	7	12.5	16.21	0.77	
Upper Screen Dipole Test (Injection)	1	2.3	0.55	4.18	4.50
	2	3.9	0.83	4.70	
	3	6.0	1.34	4.48	
	4	8.8	1.73	5.09	
	5	4.8	1.13	4.25	
	6	12.5	2.75	4.55	
	7	12.5	2.95	4.24	

Notes:

a Specific capacity was calculated by dividing pumping or recharge rate (Q) by maximum drawdown or water level rise (s).

gpm gallons per minute

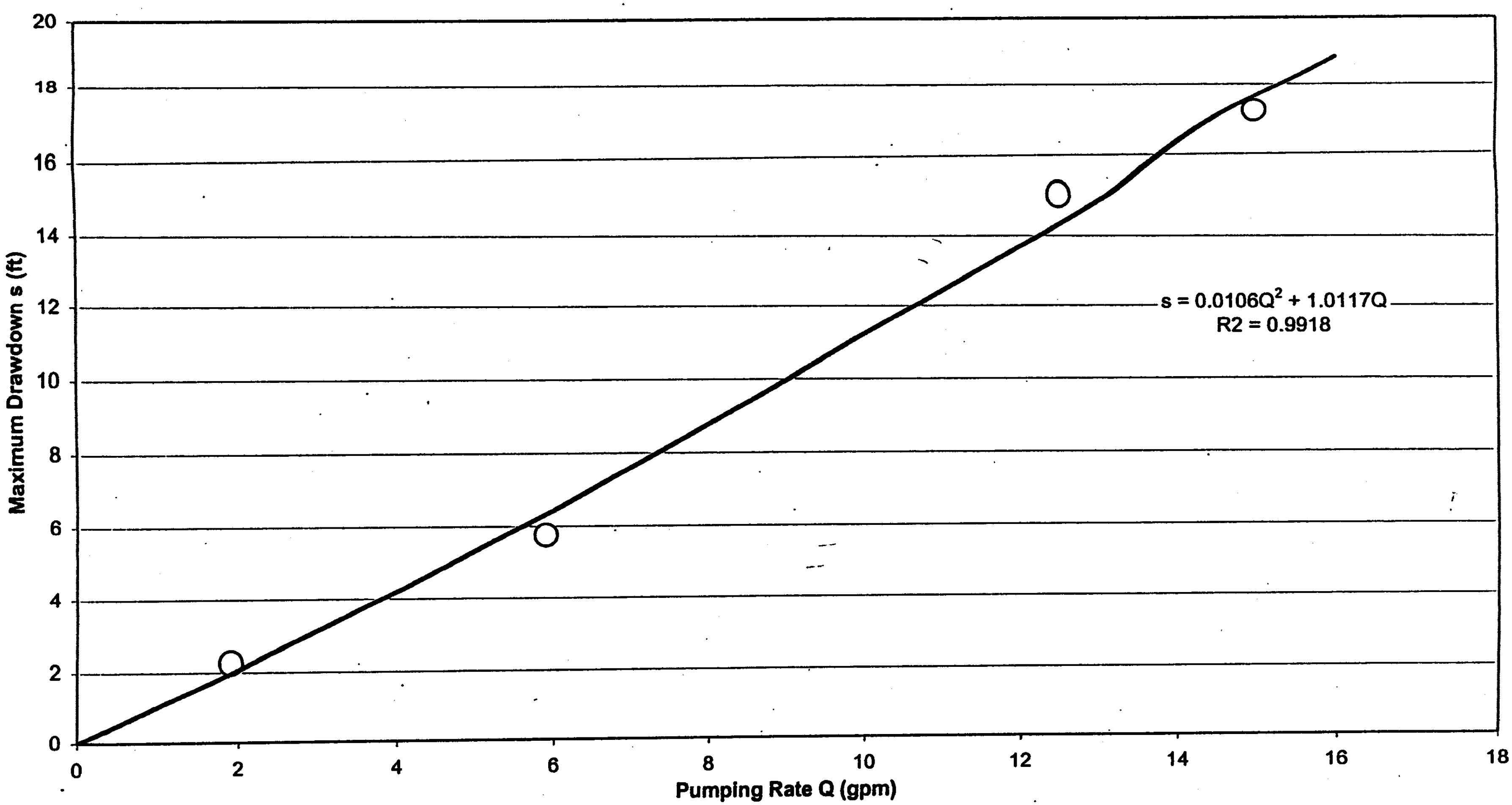
4.1.2 Well Loss and Well Efficiency

The observed total drawdown versus pumping rate (Q) was plotted and a best-fit second order polynomial function generated using the least-squares method (Figures A13, A14, A15, and A16). Based on the equation published by Rorabaugh (1953), parameters B and C are determined by the second order best-fit curves. Figures A13 and A14 show that the correlation coefficients (R^2) of the best-fit (4- and 3-point) equations based on the step test data from the lower screened interval are 0.992 (4-point) and 0.996 (3-point). The 4-point best-fit curve (Figure A13) includes all four steps of the step drawdown test, and the 3-point best-fit curve (Figure A14) only includes only data from the first three steps of the step drawdown tests. The last step of the step drawdown test may not be representative of conditions in the well and aquifer at the maximum pumping rate because drawdown reached the pump intake. The 4-point best-fit curve is included for comparison.

Figure A15 shows that the correlation coefficient (R^2) of the best-fit equation based on the dipole flow test data from the lower screened interval is 0.995. The rise in water level was used instead of drawdown for the upper screened interval injection (dipole) test (Figure A16); the correlation coefficient (R^2) of the best-fit equation based on the data from the dipole flow test from the upper screened interval is 0.984.

Water levels inside the pumping and injection well screens were not measured during hydraulic testing because of difficulties involved with isolating the two screened intervals and also because of the configuration of the pump. As a result, water levels or drawdowns were measured in piezometers GCWD and GCWS, installed within the sand packs of the lower and upper screened intervals of the GCW. Therefore, the calculated well losses and well efficiencies (Table A6) do not represent the GCW pumping or injection well screens. Instead, the values presented in Table A6 represent well losses or efficiencies between the well bore and sand packs of the GCW. Portions of the well losses could also be caused by the short (1-foot) screened intervals of piezometers GCWS and GCWD.

Results for the well efficiency calculations are presented in Table A6. As shown in the table, the calculated well efficiencies for both the lower and upper portions of the GCW are high, ranging from 78 to 96 percent. These efficiencies indicate that well losses through the sand pack are relatively low for the pumping and injection rates used in the step and dipole tests. Table A6 also indicates that the well



NOTE:
1) Data shown is from the lower screened interval of GCW.
2) Graph shown is 4 data point fit.

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Figure A13
Step Test Drawdown versus Pumping Rate and the Best Fit Equation (4-Point)

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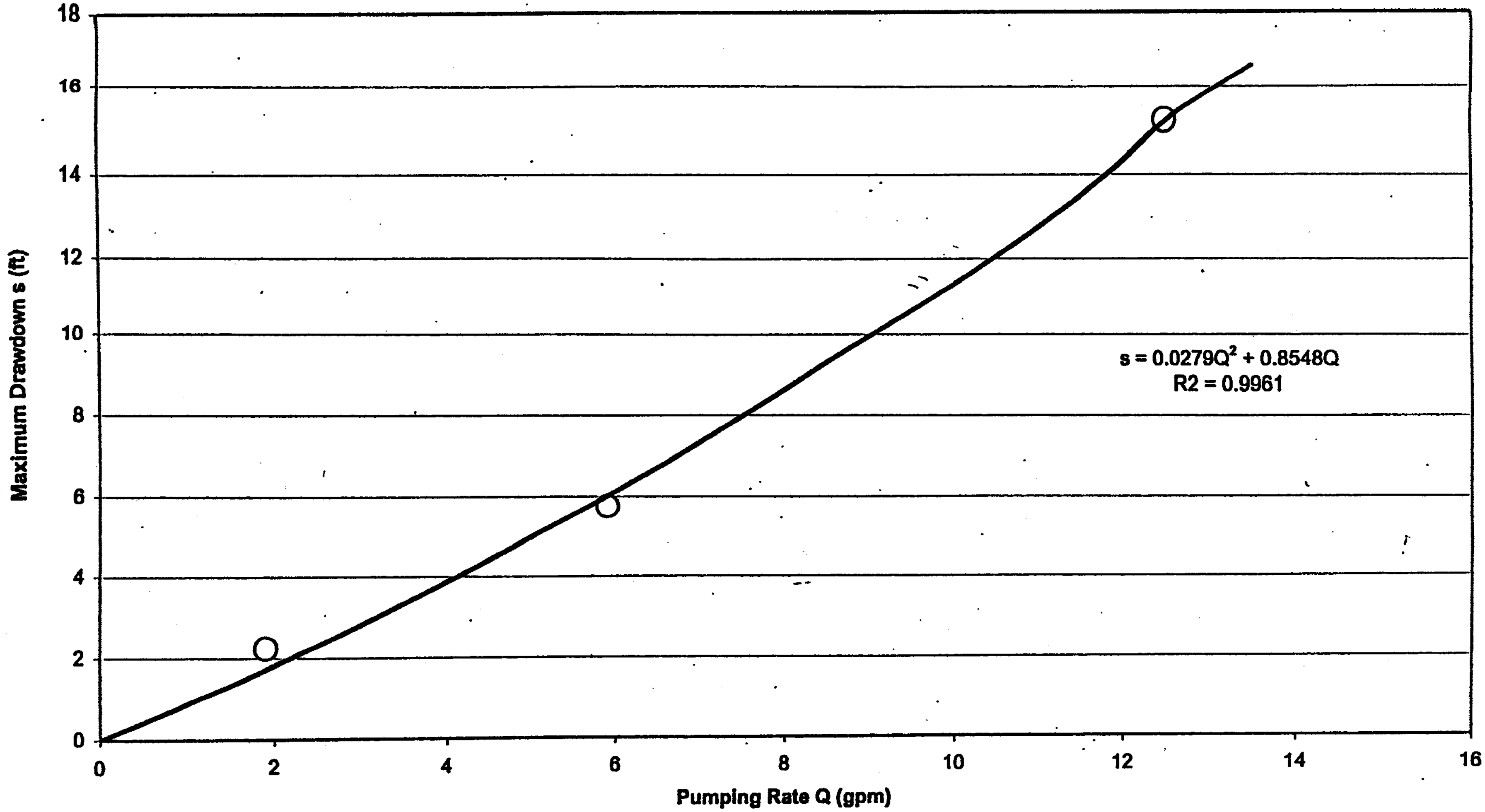

NOTE:
1) Data shown is from the lower screened interval of GCW.
2) Graph shown is 3 data point fit.

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GCW TECHNOLOGY EVALUATION

Figure A14
Step Test Drawdown versus Pumping Rate and the Best Fit Equation (3-Point)

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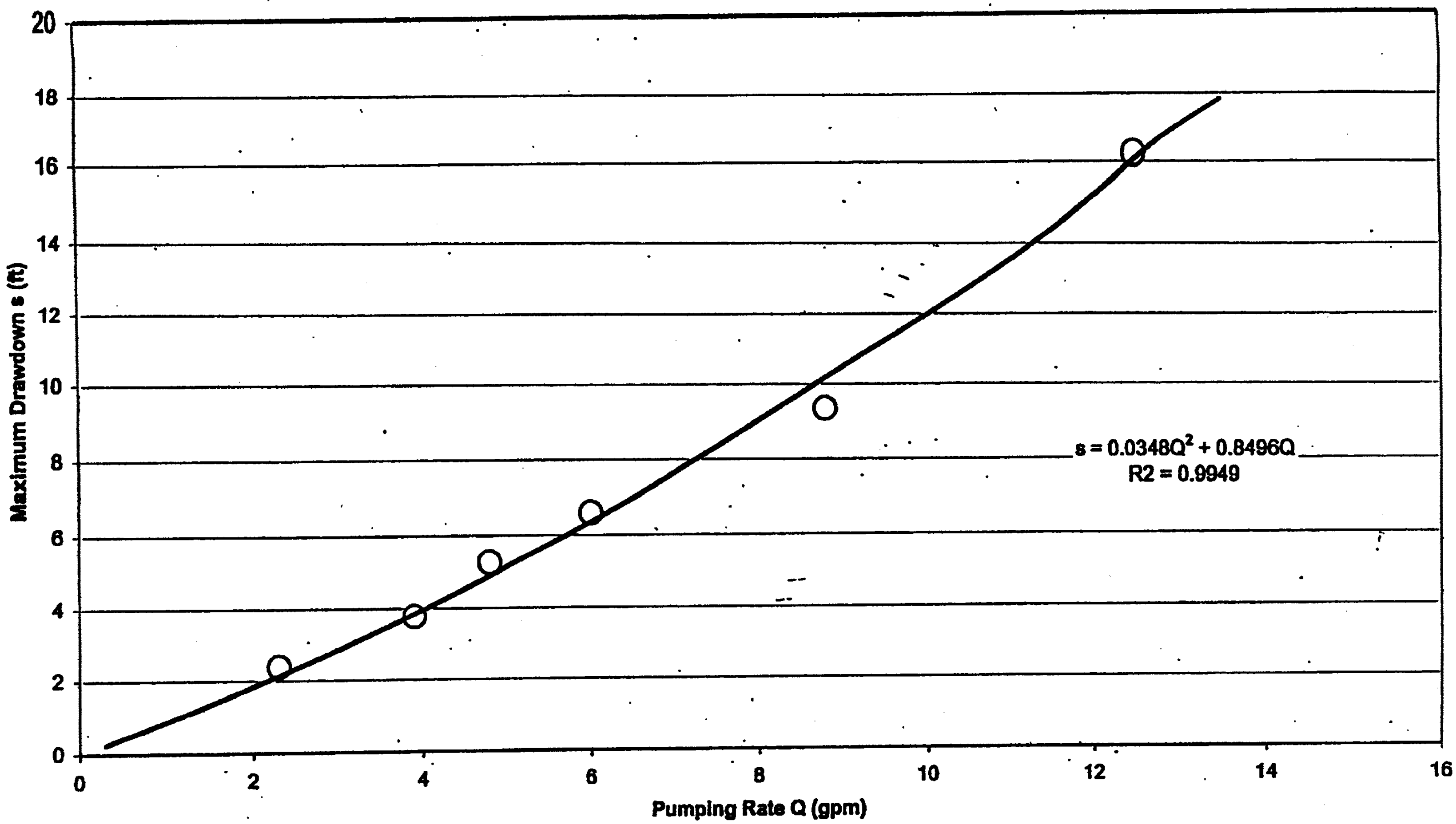

NOTE:
Data shown is from the lower screened interval of GCW.

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GCW TECHNOLOGY EVALUATION

Figure A15
Dipole Test Drawdown versus Pumping Rate and the Best Fit Equation

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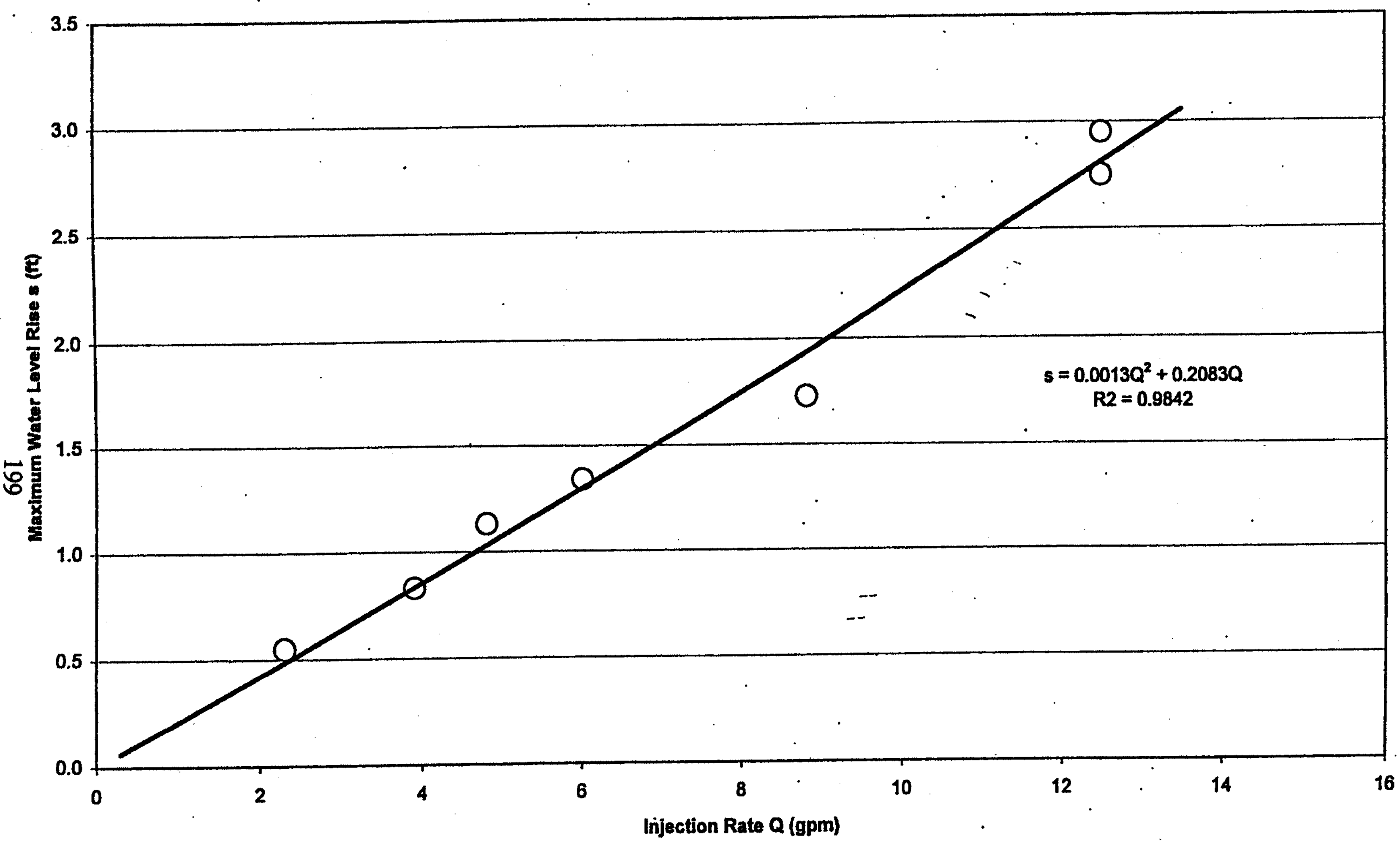

NOTE:
Data shown is from the lower screened interval of GCW.

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GCW TECHNOLOGY EVALUATION

FIGURE A16
Dipole Test Water Level Rise versus Pumping Rate and the Best Fit Equation

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TABLE A6. AQUIFER TEST DATA AND GCW SAND PACK EFFICIENCIES[1]
Cape Canaveral Air Station, Cape Canaveral, Florida

Test	Test Step	Pumping or Recharge Rate (Q) (gpm)	Measured Maximum Drawdown or Water Level Rise (s) (feet)	Sand Pack Loss Coefficient (C)	Sand Pack Loss (CQ^2) (feet)	Sand Pack Efficiency[2] (%)	Average Sand Pack Efficiency (%)
Lower Screen Step Drawdown Test (4 point fit)	1	1.9	2.24	0.0106	0.04	98	92
	2	5.9	5.75		0.37	94	
	3	12.5	15.10		1.66	89	
	4	15.0	17.11		2.39	86	
Lower Screen Step Drawdown Test (3 point fit)	1	1.9	2.24	0.0279	0.10	96	83
	2	5.9	5.75		0.97	83	
	3	12.5	15.10		4.36	71	
Lower Screen Dipole Test (Pumping)	1	2.3	2.39	0.0348	0.18	92	78
	2	3.9	3.78		0.53	86	
	3	6.0	6.60		1.25	81	
	4	8.8	9.34		2.69	71	
	5	4.8	5.24		0.80	85	
	6	12.5	16.19		5.44	66	
	7	12.5	16.21		5.44	66	
Upper Screen Dipole Test (Injection)	1	2.3	0.55	0.0013	0.01	99	96
	2	3.9	0.83		0.02	98	
	3	6.0	1.34		0.05	97	
	4	8.8	1.73		0.10	94	
	5	4.8	1.13		0.03	97	
	6	12.5	2.75		0.20	93	
	7	12.5	2.95		0.20	93	

Notes:
1) Since water levels were measured in piezometers GCWS and GCWD, installed within the sand pack of the GCW, values shown in the table represent calculated well losses or efficiencies between the well bore and the sand packs of the GCW.
2) Calculated using: $E_{well} = \frac{s - CQ^2}{s} \times 100$

gpm = gallons per minute

efficiency for the upper screened interval (injection) averages 96 percent, which is higher than the efficiency of the lower screened interval (pumping) well, which averages 78 percent.

4.2 CONSTANT RATE PUMPING TEST

This section analyzes the data from the constant discharge pumping test conducted in the lower screened portion of the GCW and presents calculations of values for various aquifer hydraulic parameters. A number of analytical models are available to analyze data from pumping tests and calculate hydraulic parameters for the aquifer. Different models were developed to simulate a variety of conditions in the aquifer. The first and most critical step in an analysis of data from a pumping test is to select an appropriate model (or models) for the specific aquifer conditions, construction of the pumping and observation wells, and configurations of the pumping test.

The analytical model for the evaluation of data from the GCW pumping test was selected based on the site hydrogeologic conceptual model, the configuration of the pumping test (including pumping and observation well construction), and the characteristics of the response to drawdown during the pumping test . Section 4.2.1 summarizes the site hydrogeology and presents the site hydrogeological conceptual model. Section 4.2.2 describes the configuration of the pumping test. Section 4.2.3 discusses the characteristics of the response to drawdown during the pumping test. Section 4.2.4 discusses selection of the analytical model, and describes the selected model and its applicability. The results of calculation for the aquifer parameters are discussed in Section 4.2.5.

4.2.1 Configuration of Constant Discharge Pumping Test

Configuration of the pumping test is important in selecting analytical models. Construction details of the pumping and observation wells, the pumping rate and duration, and the spatial orientation of the observation wells for this pumping test study are discussed in Sections 4.1 and 4.3. The configuration of the constant discharge pumping test was as follows:

- Groundwater was pumped from the isolated, lower screened interval of the GCW, which was installed at a depth of 20 to 30 feet bgs.
- The pumping well diameter is 6 inches, and the diameter of the well bore is 14 inches (including the sand pack).
- The pumping rate was kept constant at 10 gpm.

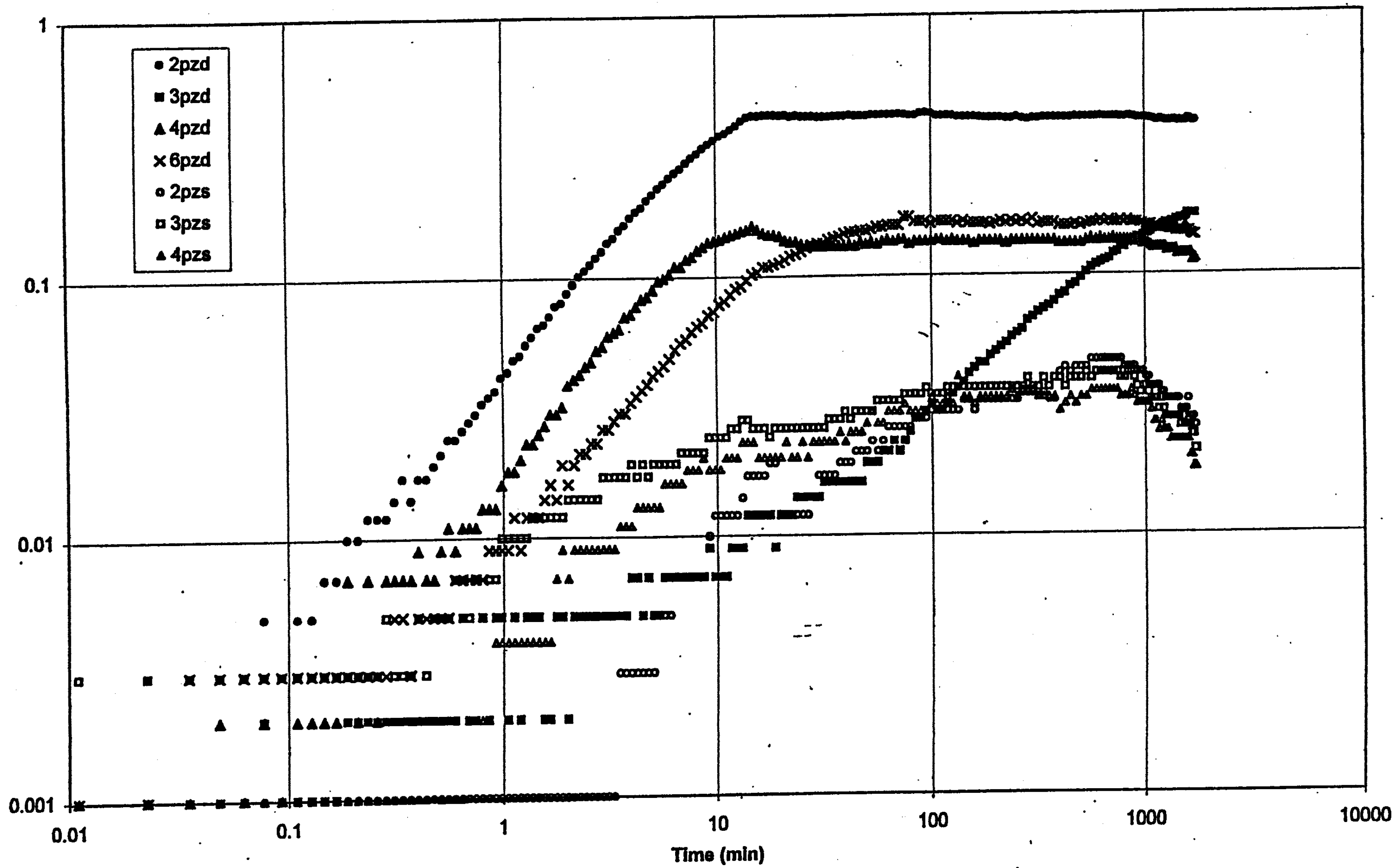
- The duration of the pumping test was 29 hours.
- The duration of the recovery period was 43 hours.
- The initial groundwater level was approximately 8 feet bgs.
- The saturated thickness of the tested aquifer is estimated at 42 feet.
- Drawdown was monitored in nine piezometers (four pairs of shallow and deep piezometers and a single deep piezometer) used as observation wells around the pumping well.
- Distances between the observation wells and the pumping well range from less than 1 foot to 30 feet
- Screens in the observation wells range from approximately 1 to 4 feet in length.
- The pumping well and the observation wells are all partially penetrating. The shallow observation wells were screened from 6 to 10 feet bgs; the deep observation wells were screened from 22 to 26 feet bgs.

4.2.2 Drawdown Response Characteristics

Drawdown data collected from the observation wells during the pumping test are plotted versus time in logarithmic and semilogarithmic scales in Figures A17 through A20. The analysis of the drawdown response in this section is intended to identify important features of the aquifer conditions or pumping test configurations such as heterogeneity and anisotropy, variations in pumping rate, leaky aquifers, positive (recharge) or negative (impermeable) boundaries, and delayed yield effects.

Table A7 summarizes the drawdown responses for the observation wells during the constant rate discharge pumping test. The initial response time is the time at which drawdown in an observation well is first positively identified.

Figures A17 and A18 indicate that observation wells constructed at different depths in the aquifer all responded to pumping in the lower aquifer zone, with later and less significant responses observed in the shallow observation wells. The pattern of the response observed in the shallow aquifer zone is consistent in all of the shallow piezometers, especially in the later-time data, with little variation occurring with distance from the pumping well. This pattern suggests that the shallow aquifer zone is laterally



NOTE: Data shown is from constant rate pumping test conducted from 9/15/00 to 9/16/00.

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GCW TECHNOLOGY EVALUATION

FIGURE A17
Drawdown versus Time
Under Pumping Conditions
(Log-Log Plot)

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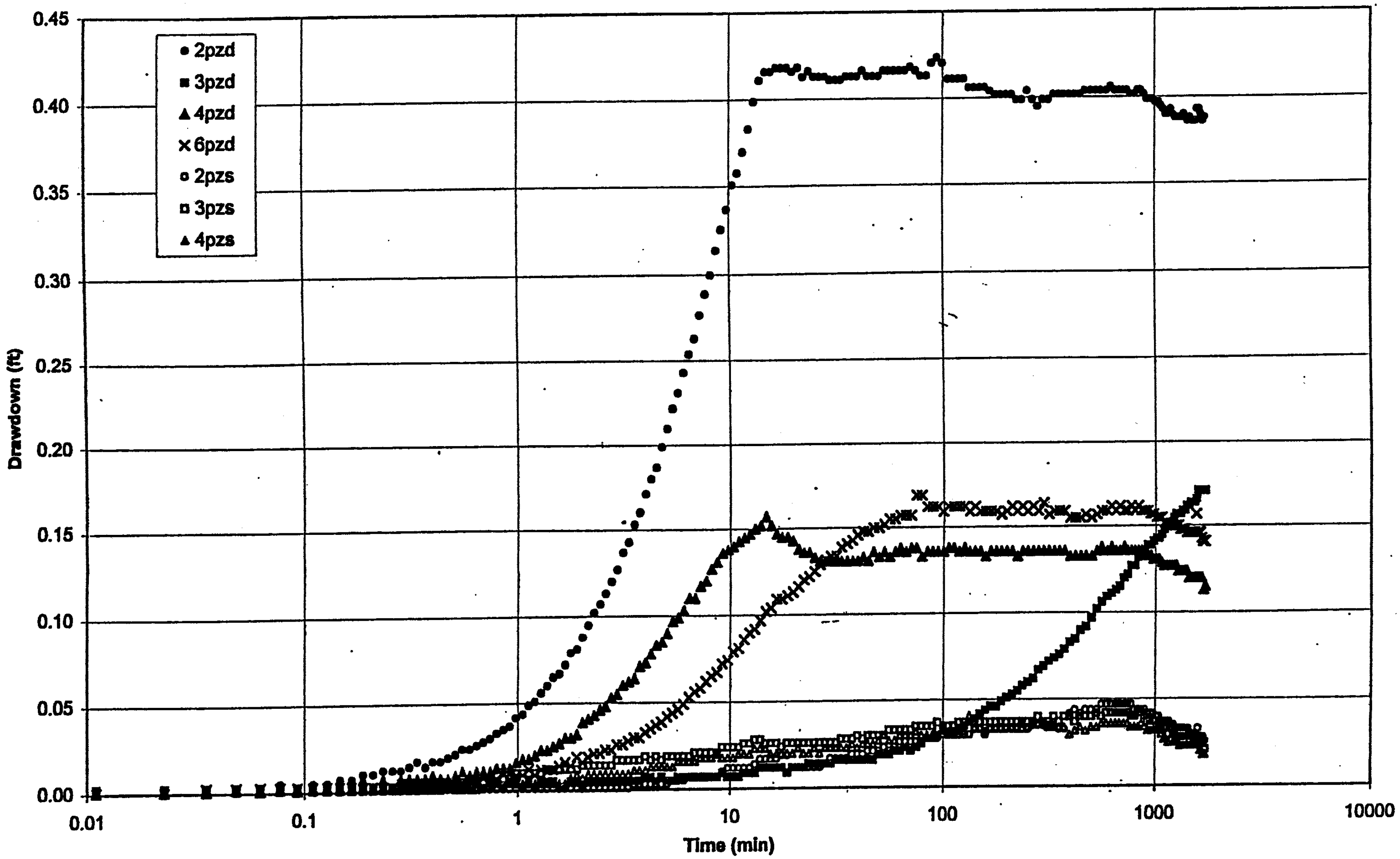
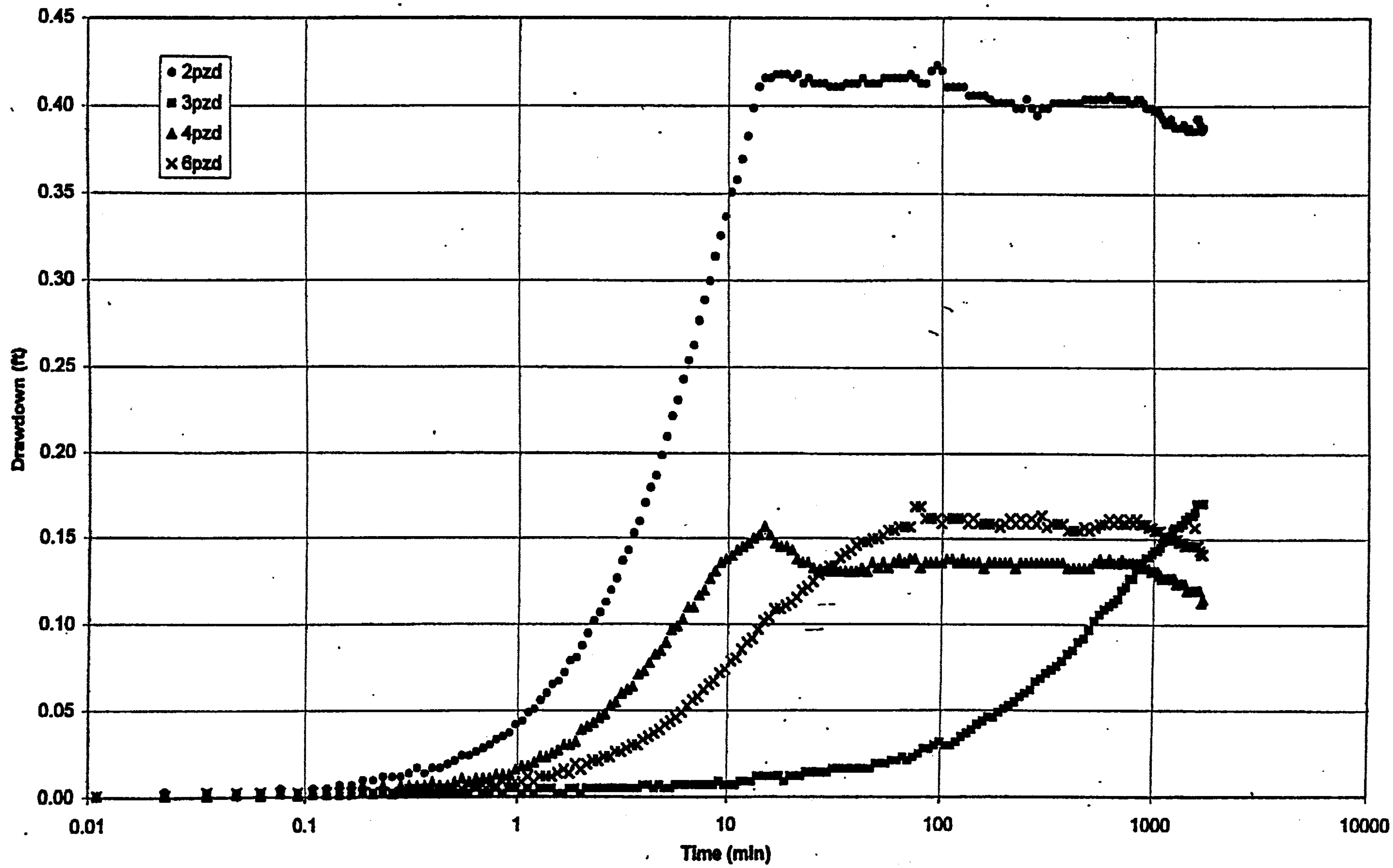


NOTE: Data shown is from constant rate pumping test conducted from 9/15/00 to 9/16/00.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA
GCW TECHNOLOGY EVALUATION

FIGURE A18
Drawdown versus Time
Under Pumping Conditions
(Semi-Log Plot)

Tetra Tech EM Inc.



NOTE: Data shown is from constant rate pumping test conducted from 9/15/00 to 9/16/00.

FACILITY 1381, CCAS, CAPE CANAVERAL, FLORIDA GCW TECHNOLOGY EVALUATION
FIGURE A20 **Drawdown versus Time** **In Deep Aquifer Zone Under Pumping Conditions** **(Semi-Log Plot)**
Tetra Tech EM Inc.

TABLE A7. CONSTANT RATE DISCHARGE PUMPING TEST INFORMATION
Cape Canaveral Air Station, Cape Canaveral, Florida

Observation Well ID	Distance from GCW (1) (in feet)	Depth of Screened Interval (in feet)	Measured Maximum Drawdown (in feet)	Initial Response Time (2) (in minutes)
DEEP AQUIFER ZONE (PUMPED INTERVAL) PIEZOMETERS				
GCWD	0.5	24.5 – 26.0	15.33	0.023
2PZD	10.55	21.3 – 24.6	0.42	0.23
3PZD	14.56	22.7 – 26.0	0.17	13.88
4PZD	21.04	22.6 – 25.9	0.16	0.64
6PZD	30.14	22.7 – 26.0	0.17	1.12
SHALLOW AQUIFER ZONE PIEZOMETERS				
GCWS	0.5	6.5 – 8.0	0.05	0.74
2PZS	11.77	6.5 – 9.8	0.05	9.76
3PZS	14.13	6.2 – 9.5	0.04	2.02
4PZS	20.51	6.2 – 9.5	0.04	3.54

1) The GCW was the pumping well.
2) The initial response time is the elapsed time at which a 0.01 foot change in drawdown first occurred.
3) Piezometer GCWS went dry during the constant rate pumping test.

homogeneous and that a vertical hydraulic connection exists between the shallow and deep aquifer zones. Drawdown in the shallow observation wells display a typical delayed response in the water table at approximately 20 minutes into the test.

At approximately 50 minutes into the pumping test, drawdown begins to stabilize in the observation wells in the deep aquifer zone, while drawdown in the shallow observation wells starts to increase. At 900 minutes into the test, drawdowns in both the deep and shallow aquifer zones decreased dramatically, suggesting that the influence of the pumping well may have intersected a recharge boundary, or indicating significant delayed yield from the upper aquifer zone.

Responses in the observation wells in the deep aquifer zone showed more variation with distance. The most significant response was observed in piezometer 2PZD, which is closest to the pumping well. Later-time data in piezometer 6PZD indicated a larger response than was observed at piezometer 4PZD, which is closer to the pumping well. Early water level data for piezometer 3PZD indicate a delayed response to pumping in the lower screened interval, with drawdown increasing significantly at 100 minutes into the test and following a linear increase pattern. Because the pressure transducer in 3PZD was replaced before the pumping test began, the observed response is not expected to be a result of equipment malfunction.

The following summarizes the drawdown responses of the piezometers during the constant rate pumping test:

- Drawdown responses were identified in all of the observation wells, which are within a radius of 30 feet from the pumping well; positive identification of drawdown response is defined as drawdown that exceeds 0.01 feet (any data recorded below 0.01 feet would be expected to include significant error attributable to the transducer or data logger).

- Early drawdown responses in the observation wells show that the data plots do not closely follow a type curve; the intermediate and later data indicate possible delayed responses in the shallow aquifer zone and vertical leakage from the shallow to the deep aquifer zones.

4.2.3 Selection of Analytical Model

Based on the site hydrogeological conceptual model, the configuration of the pumping test, and drawdown response analysis discussed above, the tested aquifer is considered a thick unconfined aquifer with significant heterogeneity at different depths. In general, the shallow aquifer zone is significantly (by an order of magnitude) more transmissive than the deep aquifer zone. The deep aquifer zone tested received primarily vertical recharge from the shallow aquifer zone during the test. The vertical recharge is probably more significant than the horizontal flow toward the pumping well because of the lower transmissivity of the deep aquifer zone. In addition, both the pumping well and the observation wells partially penetrate the aquifer zones. The upper portion of the pumping well screen may intersect zones of higher permability than the lower portion of the pumping well screen. These factors make it more difficult to select and apply appropriate analytical methods to interpret the pumping test data.

Based on the evaluation of the observation well drawdown patterns and aquifer hydrogeological conceptual model, the Hantush-Jacob (Hantush and Jacob 1955) and Hantush (1960) models for leaky aquifers were selected as appropriate for the analysis of data from the pumping test. Neuman's delayed yield model (1974) was also used to analyze the pumping data portion (the deep aquifer zone) of the data from the dipole flow test, assuming insignificant impacts of injection to the shallow aquifer zone.

Aquifer hydraulic parameters from the analysis of data from the pumping test using the leaky aquifer models are considered overestimated for the deep aquifer zone because the vertical leakage is more significant during the test than the model assumes. In addition, vertical recharge from the shallow aquifer zone may have been dominant at later stages of the test so that the lateral flow in the pumped aquifer zone became less significant. The hydraulic conductivity values calculated may therefore represent an average of the vertical hydraulic conductivities of the shallow aquifer zone and horizontal hydraulic conductivities of the deep aquifer zone. Results using Neuman's delayed yield model may be more representative of the hydraulic parameters for the deep aquifer zone.

4.2.4 Results

Based on the site hydrogeological conceptual model, the configuration of the pumping test, and the analysis of drawdown responses discussed previously, the aquifer tested is considered a 40 feet thick and unconfined with significant heterogeneity at various depths. In general, the shallow aquifer zone is significantly (by an order of magnitude) more transmissive than the deep aquifer zone. The deep aquifer zone tested received primarily vertical recharge from the shallow aquifer zone during the test. The vertical recharge is probably more significant than the horizontal flow toward the pumping well because of the lower transmissivity of the deep aquifer zone. In addition, both the pumping well and the observation wells partially penetrate the various zones of the aquifer. The upper portion of the pumping well screen may intersect zones of higher permeability than the lower portion of the pumping well screen. These factors make it more difficult to select and apply appropriate analytical methods to interpret the data from the pumping test.

Based on the evaluation of the observation well drawdown patterns and aquifer hydrogeological conceptual model, the Hantush-Jacob (1955) and Hantush (1960) models for leaky aquifers were selected as appropriate for the analysis of the data from the pumping test. The Neuman delayed yield model (1974) was also used to analyze the pumping portion (deep aquifer zone) of the data for the dipole flow test, assuming insignificant or negligible impacts of injection to the shallow aquifer zone.

Hydraulic parameters of the aquifer inferred from the analysis of the data for the pumping test using the leaky aquifer models are considered overestimated for the deep aquifer zone because the vertical leakage is more significant during the test than the model assumes. In addition, vertical recharge from the shallow aquifer zone may have been dominant at later stages of the test so that the lateral flow in the aquifer zone pumped became less significant. The calculated hydraulic conductivity values may represent an average of the vertical hydraulic conductivities of the shallow aquifer zone and horizontal hydraulic conductivities of the deep aquifer zone. Results using the Neuman delayed yield model may therefore be more representative of the hydraulic parameters of the deep aquifer zone.

Aquifer hydraulic parameters were calculated using the groundwater pumping test data analysis software package AQTESOLV™ (Duffield and Rumbaugh 1991; HydroSOLVE, Inc. 1996). Log-log plots of drawdown versus time were prepared, and the plots were matched visually with the Hantush-Jacob, Hantush, and Neuman type curves. The automatic matching option (using the least-square computational approach) offered by AQTESOLV™ was not used because the computational method is insensitive to the early data match and is biased toward the data in the late stages of the test.

Attachment A includes log-log drawdown plots and the curve matching of data from the observation wells generated using AQTESOLV, which are presented in this report.

Table A8 presents the results of the calculations of the hydraulic parameters of the aquifer. The calculated hydraulic parameters for the aquifer based on analysis of the pumping test data are summarized as follows:

- The calculated aquifer transmissivity ranges from approximately 1,790 to 2,190 square feet per day (ft^2/day) based on analysis using the Hantush-Jacob model. This result is considered higher than the average transmissivity of the deep aquifer zones because of significant recharge (that is, more than normal leakages) from the shallow aquifer zone.

- The hydraulic conductivity of the shallow aquifer zone, calculated using the transmissivities provided previously and based on the estimated saturated aquifer thickness of 41.7 feet, ranges from 42.9 to 52.5 feet per day. This range of hydraulic conductivity values is typical for clean sand (Freeze and Cherry 1979), which is consistent with the lithology of the shallow aquifer zone at the site.

- The transmissivity of the deep aquifer zone, as calculated from dipole flow test data using the Neuman delayed yield model, ranges from 196 to 337 ft^2/day.

- The hydraulic conductivity of the deep aquifer zone, calculated using the transmissivities provided above and based on an estimated saturated aquifer thickness of 42 feet, ranges from 4.6 to 10.5 feet per day.

- Using the results for the Hantush-Jacob model, the estimated aquifer storativity ranges from 0.03 to 0.07, a typical value range for the average of specific yield and storativity of an unconfined aquifer.

- The specific yield of the aquifer tested ranges from 0.06 to 0.09, based on the Neuman delayed yield model calculation. The storativity values using Neuman's model range from 0.006 to 0.007.

Generally, the estimated values for hydraulic conductivity of the aquifer may represent the average horizontal properties of the aquifer tested. The hydraulic conductivity values calculated from data for the observation wells near the pumping well may be more representative of the vertical hydraulic properties of the shallow aquifer zone because of vertical recharge near the pumping well.

TABLE A8

AQUIFER HYDRAULIC PARAMETERS

Cape Canaveral Air Station, Cape Canaveral, Florida

Observation Well	Hantush-Jacob (1955)			Hantush (1960)			Neuman (1977)			
	T (ft^2/day)	S	r/B	T (ft^2/day)	S	β	T (ft^2/day)	S	Sy	β
CONSTANT RATE PUMPING TEST RESULTS[1]										
2PZD	1,789.2	0.07	0.5	--	--	--	--	--	--	--
3PZD	--	--	--	1,421.6	0.08	5.6	--	--	--	--
4PZD	2,191.2	0.03	1.0	--	--	--	--	--	--	--
6PZD	2,167.6	0.03	0.7	--	--	--	--	--	--	--
DIPOLE TEST #6 RESULTS (ANALYZED AS CONSTANT RATE PUMPING TEST)										
2PZD	2,027.5	0.13	0.4	556.1	0.0007	8.0	--	--	--	--
4PZD	--	--	--	--	--	--	337	0.006	0.09	1.5
6PZD	--	--	--	--	--	--	196	0.007	0.06	3.0
DIPOLE TEST #7 RESULTS (ANALYZED AS CONSTANT RATE PUMPING TEST)										
2PZD	2,082.1	0.13	0.4	--	--	--	--	--	--	--
4PZD	3,675.4	0.06	0.8	--	--	--	--	--	--	--
6PZD	4,682.9	0.11	1.2	--	--	--	--	--	--	--

Notes:
1) Results shown are from deep aquifer zone.

4.3 DIPOLE FLOW TESTS

The dipole flow test (DFT), a new single-well hydraulic test for aquifer characterization, was first proposed by Kabala (1993). The test was designed to characterize the vertical distribution of local horizontal and vertical hydraulic conductivities near the test well. Measures of the aquifer's anisotropy ratio and storativity can also be obtained through analysis of data from the DFT. DFT is a cost-effective method for to characterize the hydraulic properties of an aquifer because (1) the duration of the test is short; the test generally lasts no more than a few hours, and (2) no investigation-derived waste is generated because the water from the pumping chamber is injected to the aquifer through a recharge chamber.

4.3.1 Configuration of Dipole Flow Tests

The dipole flow test configurations for Dipole Tests 6 and 7 are summarized as follows:

- Groundwater was pumped from the isolated, lower screened interval of the GCW, which was installed at a depth of 20 to 30 feet bgs.
- Groundwater was reinjected into the upper screened interval of the GCW, which was installed at depth of 5 to 10 feet bgs.
- The diameter of pumping well is 6 inches, and the diameter of the well bore is 14 inches (including the sand pack).
- The pumping and injection rate was held constant at approximately 12.5 gpm.
- The duration of Dipole Test 6 was 2 ½ hours.
- The duration of Dipole Test 7 was 6 hours.
- The initial groundwater level was 8 feet below ground surface, and was flat.
- The saturated thickness of the tested aquifer is estimated to be 42 feet.
- Drawdown was monitored in nine piezometers (four pairs of shallow and deep piezometers and a single deep piezometer) using pressure transducers and data loggers
- Distances between the piezometers and the GCW range from less than 1 foot to 30 feet
- The screens in the piezometers range from 1 to 4 feet in length.

- The pumping well and the observation wells are all partially penetrating. The shallow piezometers were screened from 6 to 9 feet below ground surface; the deep piezometers were screened from 22 to 26 feet below ground surface.

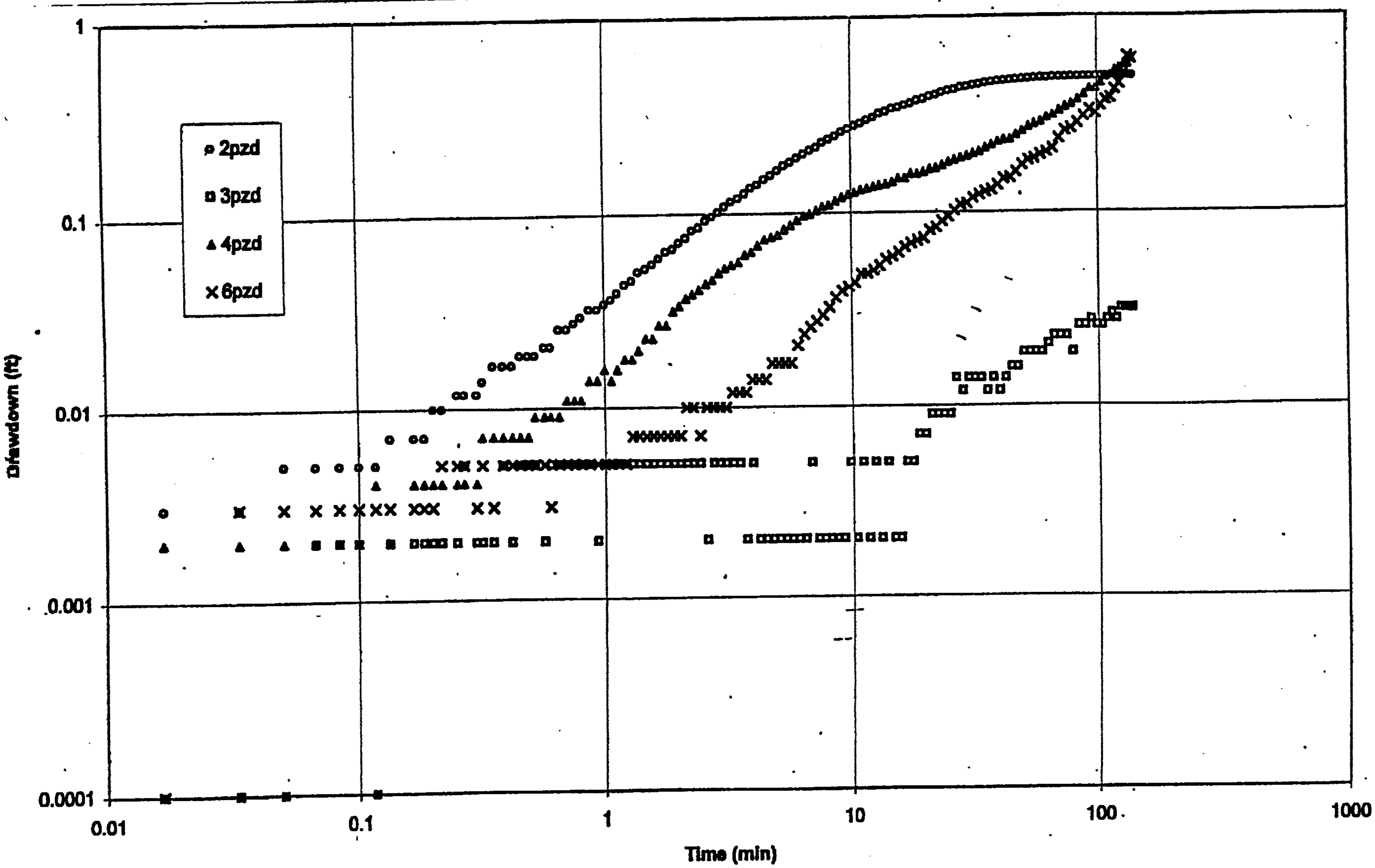
4.3.2 Results of Hydraulic Monitoring During Dipole Testing

Drawdown data collected from the observation wells during the dipole testing are plotted versus time in a logarithmic scale in Figures A21 through A24.

The drawdown plot from deep aquifer zone piezometers during Dipole Test 6 (Figure A21) indicate that the response time varied proportionally with distance from the GCW in each of the piezometers except for 3PZD. Piezometer 3PZD shows a delayed response as well as lower drawdown than observed in the other piezometers. The behavior observed in piezometer 3PZD during the dipole flow testing is similar to the constant rate pumping test. This behavior suggests that the piezometer is screened in a less permeable or less well-connected zone than the pumping well or was inappropriately constructed.

Drawdowns observed in piezometers 2PZD, 4PZD, and 6PZD were similar and increased at similar rates until about 20 minutes into the test, when the drawdown in piezometer 2PZD began to stabilize or even decrease slightly while drawdowns in 4PZD and 6PZD began to increase at a faster rate. The drawdown curves cross at approximately 110 minutes into the test, indicating that the drawdown in piezometer 2PZD was then less than was observed farther from the GCW. The intersection of the curves suggests that injection in the upper portion of the GCW may have been affecting the deep aquifer zone as much as 10 feet away from the GCW.

After Dipole Test 6 ended and a recovery period lasting 3.5 hours was allowed, Dipole Test 7 was started at the same pumping rate as Dipole Test 6 (12.5 gpm). Drawdown curves for piezometers 2PZD, 4PZD and 6PZD, shown in Figure A22, are less steep than were plotted for the same piezometers during Dipole Test 6. As with Dipole Test 7, however, drawdowns in the 3 piezometers are proportional to distance from the GCW. The three drawdown curves begin to stabilize at about 30 to 40 minutes into Dipole Test 7 and then start to decrease at about 350 minutes, just before the test was terminated. Piezometer 6PZD, which is farthest from the GCW, shows the earliest and most dramatic decrease in drawdown. The difference in the responses of the piezometers between Dipole Test 6 and Dipole Test 7 is shown in Figures A23 and A24, which are comparisons between the two tests, as measured in piezometers 4PZD



NOTE: Data shown is from Dipole Test 6 conducted on 9/18/00

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FIGURE A21
Drawdown versus Time
in Deep Aquifer Zone During Dipole Test 6
(Log-Log Plot)

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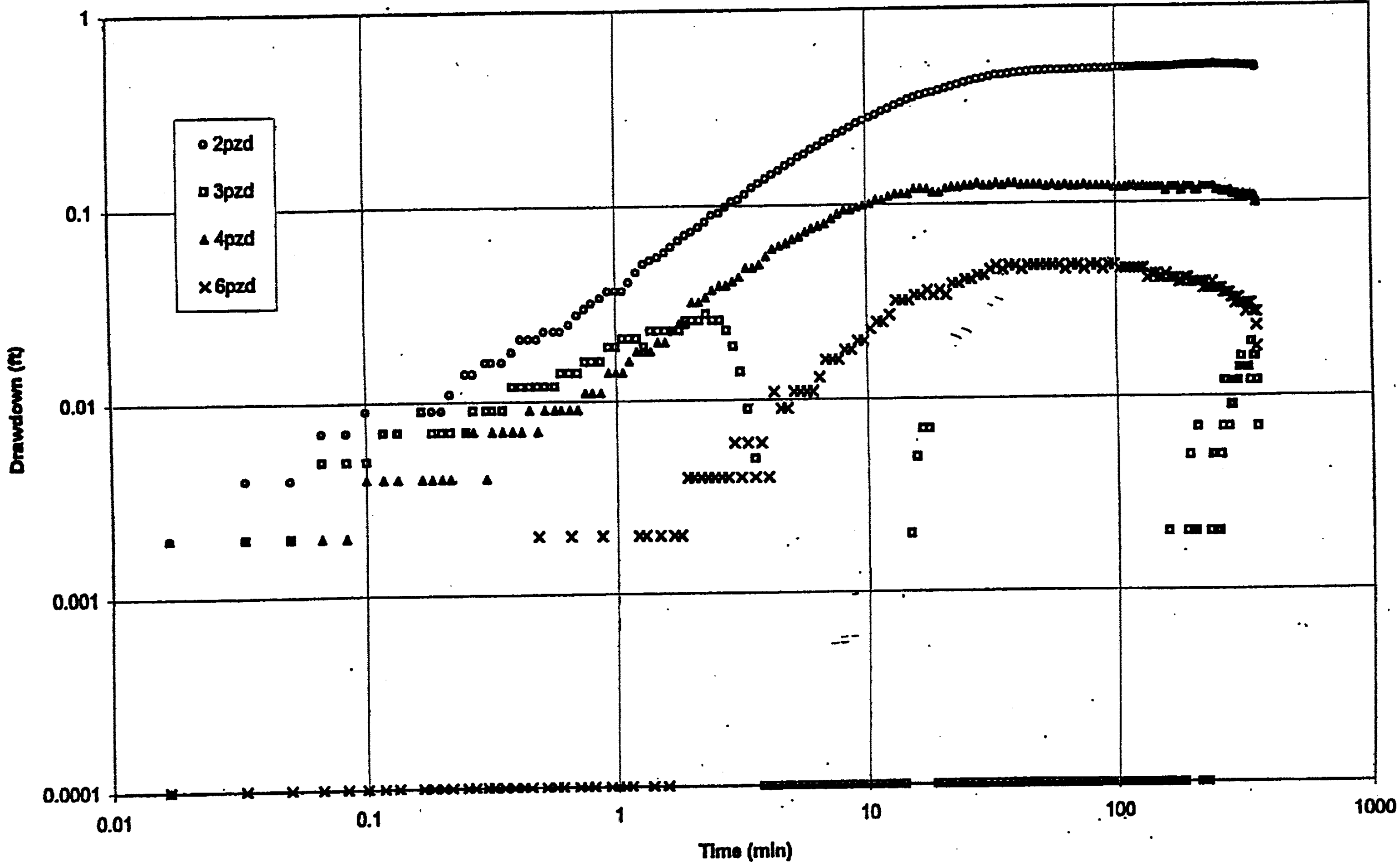

NOTE: Data shown is from Dipole Test 7 conducted on 9/18/00

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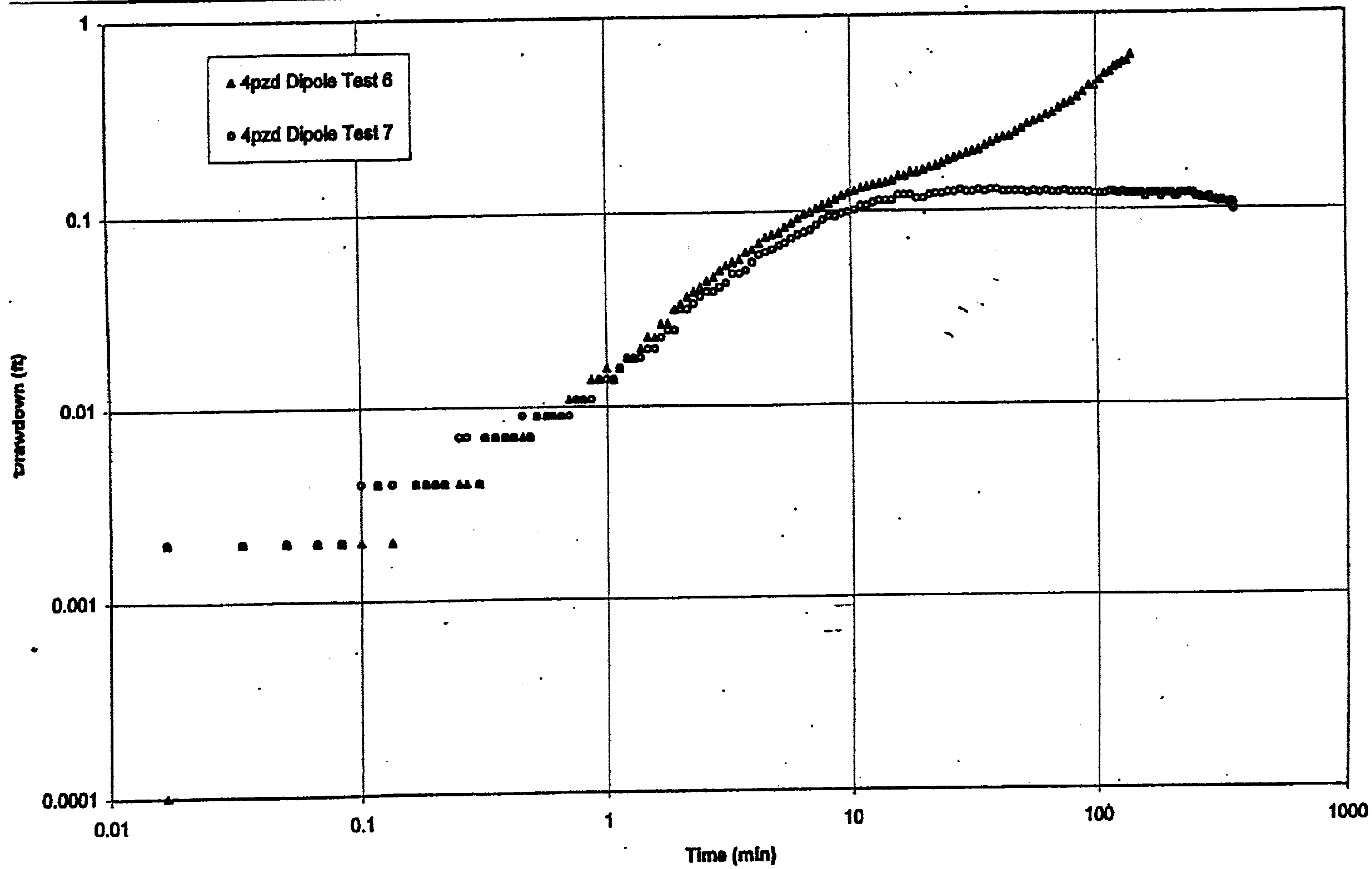
GCW TECHNOLOGY EVALUATION

FIGURE A22
Drawdown versus Time
in Deep Aquifer Zone During Dipole Test 7
(Log-Log Plot)

Tetra Tech EM Inc.



NOTE: Data shown is from Dipole Tests 6 and 7 conducted on 9/18/00

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FIGURE A23
Drawdown versus Time
at Piezometer 4pzd During Dipole Test 6 and 7
(Log-Log Plot)

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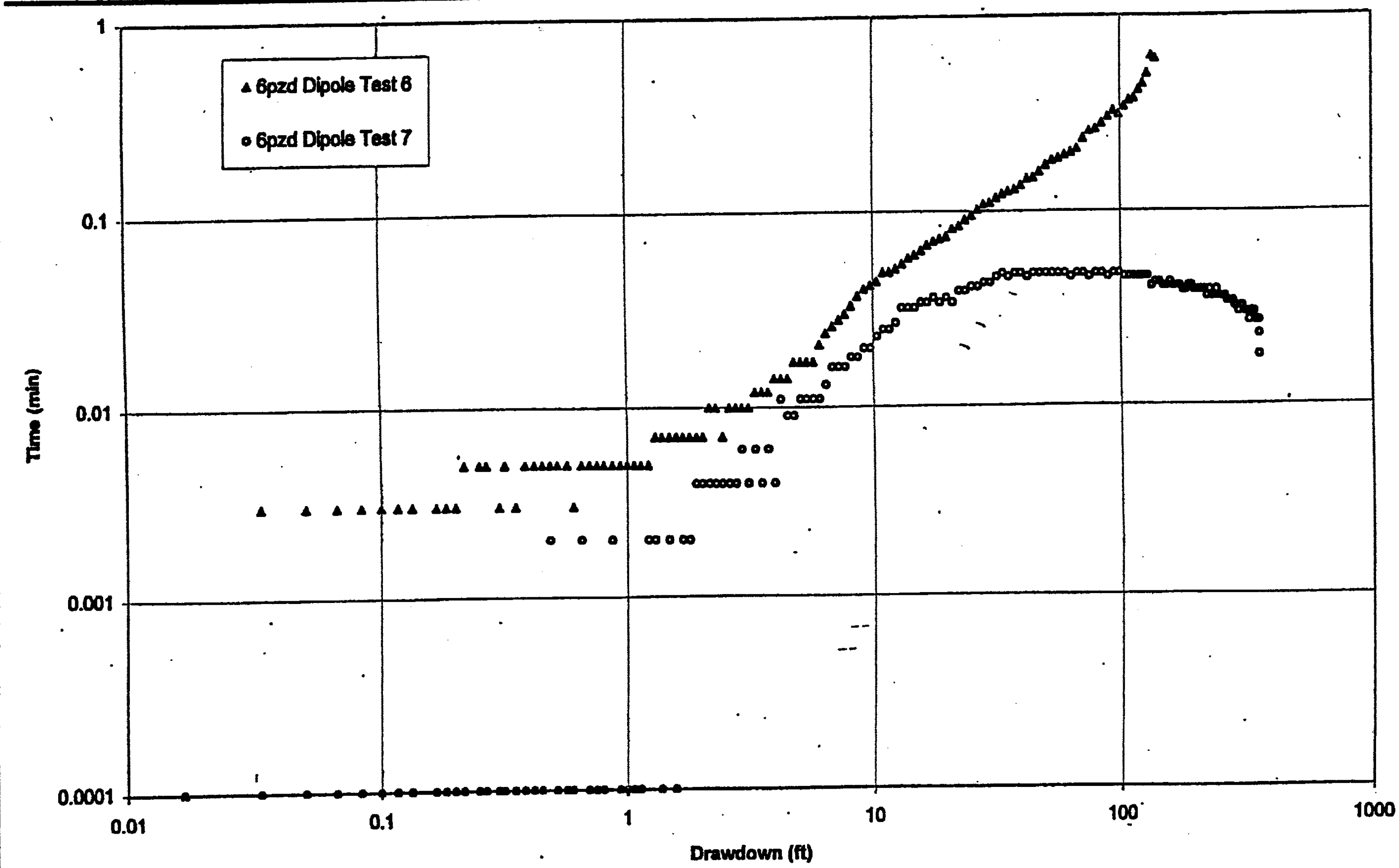

NOTE: Data shown is from Dipole Tests 6 and 7 conducted on 9/18/00

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GCW TECHNOLOGY EVALUATION

FIGURE A24
Drawdown versus Time
at Piezometer 6pzd During Dipole Test 6 and 7
(Log-Log Plot)

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TABLE A9

DIPOLE FLOW TEST STEADY STATE SOLUTIONS USING KABALA (1993 AND 1997) METHODOLOGY

WELL	DISTANCE (FEET)	MAXIMUM DRAWDOWN (1) (FEET H_2O)	GENERAL SOLUTION BEST MATCH ANISOTROPIC VALUE (K_r/K_z) (KABALA 1993)	LARGE WELLBORE SOLUTION BEST MATCH ANISOTROPIC VALUE (2) (K_r/K_z) (XIANG AND KABALA 1997)
GCWS	0.5	-2.948	0.64	0.64
GCWD	0.5	16.259	could not match	could not match
2PZS	10	-0.046	0.35	0.35
2PZD	10	0.475	7.29	7.29
3PZS	15	-0.046	0.80	0.80
3PZD	15	0.014 (3)	0.31	0.31
4PZS	20	-0.193	5.06	5.06
4PZD	20	0.099	2.76	2.76
6PZD	30	0.027	1.93	1.93
Average			**2.39**	**2.39**

(1) Negative value denotes increase in water level
(2) The Large Borehole Correction did not significantly change the value of the anisotropic ratio.
(3) PZ3D did not reach steady state during the 1700 minute long term extraction test and may not have reached steady state conditions during the 360 minute Dipole Test 7.

and 6PZD. These results suggest that injected groundwater flowed vertically from the shallow aquifer zone to the deep aquifer zone during the recovery period.

4.3.3 Dipole Flow Test Data Interpretation and Aquifer Anisotropy Estimation

The purpose of dipole testing is to determine the aquifer anisotropic ratio. During the dipole test, a pump was placed at the lower screen of the GCW. Water is metered as it flows from the lower to the upper screen. Pressure transducers record water level changes in the piezometers surrounding the GCW. Burns (1969) and Weeks (1969) were among the first to propose dipole testing. More recently, Kabala (1993); Zlotnik and Ledder (1996); Xiang and Kabala (1997); Zlotnik and Zurbuchen (1998); and Sutton et al. (2000) all have proposed solutions to the dipole testing method. The actual field-scale anisotropic ratio is rarely measured. Hvilshøj, Jensen and Madsen (2000) performed a field-scale test to compare the Kabala (1993) solution to a numerical solution.

Dipole flow tests were performed using the CCAS GCW on September 14 and 18. The test on September 14 was a step test conducted at 2.3, 3.7, 6.0, 8.8 and 4.8 gpm. The reason for the step dipole test was to determine the maximum flow rate that the GCW could sustain recirculating conditions. The Dipole test conducted at 12.5 gpm on September 18 was designed for a longer period of time. The test was inadvertently stopped after 142 minutes because of a power failure and resumed after 210 minutes. This analysis is concerned with the final dipole test, Dipole Test 7, conducted using a pumping rate of 12.5 gpm for 360 minutes.

Herrling et al. (1991) found that the size of a circulation cell around a GCW was strongly dependent on the aquifer anisotropic ratio, the ratio of the horizontal to vertical conductivity. Herrling and Stamm (1992) developed a numerical model to describe the flow of a circulation cell utilizing the anisotropic ratio. Phillip and Walter (1992) and Macdonald and Kitanidis (1993) proposed analytical models.

Zlotnik and Ledder (1996) found the five possible boundary conditions for dipole flow tests:

1) If the nearest aquifer boundary is far outside the region of influence, dipole flow can be described using a model of an aquifer of infinite extent. Zlotnik and Ledder (1996) have two examples of infinite extent aquifer solutions.

2) If only one horizontal impermeable or low-permeable bed is near the region of influence, a model of a confined sem-infinite aquifer is appropriate. Zlotnik and Ledder (1996) have an example of semi-infinite extent aquifer solutions.

3) If the water table is near the region of influence, but a horizontal confining bed is not, the unconfined semi-infinite aquifer model is appropriate. The drawdown induced by the dipole depends in the distance to the water table and should be calculated using an appropriate boundary condition at the moving surface. Zlotnik and Ledder (1996) and Zlotnik and Zurbuchen (1998) discuss this configuration.

4) If both upper lower horizontal impermeable or low permeable boundaries are near the region of influence, then the Kabala (1993) and Xiang and Kabala (1997) aquifer models are appropriate. The Burns Solution (1969) has an upper and lower boundaries on an otherwise infinite aquifer and is also appropriate.

5) If the water table and a lower horizontal confining bed are both near the region of influence, an unconfined aquifer model should be applied. The Burns (1969) solution, for an infinite aquifer in the areal extent but close to the water table and lower horizontal confining bed, is applicable. Neuman's (1974) well functions can be utilized if the circulation flow rate is small. Otherwise more complex nonlinear flow models should be applied (Macdonald and Kitanidis, 1993). The Kabala (1993) and Xiang and Kabala (1997) solutions can also be modified for unconfined aquifer conditions.

The conditions for the CCAS GCW are most similar to condition #5. Kabala (1993) developed a dipole flow test method that was first field tested on a GCW in North Island (Simon et al 2000). All nomenclature is described in the notations (Appendix B). For a GCW that injects from the upper screen and extracts from the lower, the head change can be described by:

$$s(t)_{upper} = \frac{Q}{\pi K_r b}\sum_{n-1}^{\infty}\left[\left(\frac{\sin(n\pi\Delta_{upper}/b)}{n\pi\Delta_{upper}/b}\right)^2 \sin\left(\frac{n\pi(\ell+d)}{2b}\right)\right.$$

$$\left.\bullet \sin\left(\frac{n\pi(\ell-d-2\Delta_{upper})}{2b}\right)\cos\left(\frac{n\pi(d+\Delta_{upper})}{b}\right)W\left(\frac{r_w^2 S_s}{4K_r t};\sqrt{\frac{K_z}{K_r}}\frac{n\pi r_w}{b}\right)\right] \quad (1)$$

Similarly for the lower:

$$s(t)_{lower} = \frac{-Q}{\pi K_r b}\sum_{n=1}^{\infty}\left[\left(\frac{\sin(n\pi\Delta_{lower}/b)}{(n\pi\Delta_{lower}/b}\right)^2 \sin\left(\frac{n\pi(\ell+d)}{2b}\right)\right.$$

$$\left.\bullet \sin\left(\frac{n\pi(\ell-d-2\Delta_{lower})}{2b}\right)\cos\left(\frac{n\pi(d+\Delta_{lower})}{b}\right)W\left(\frac{r_w^2}{4K_r t};\sqrt{\frac{K_z}{K_r}}\frac{n\pi r_w}{b}\right)\right] \quad (2)$$

The steady state solution in the upper chamber reduces to:

$$s(r)_{upper} = \frac{2Q}{\pi K_r b}\sum_{n=1}^{\infty} R_n K_0(n\rho / a) \quad (3)$$

where:

$$R_n = \left[\frac{\sin(n\delta)}{n\delta}\right]^2 \sin\left[n(\frac{\alpha}{2}+\beta)\right]\sin\left[n(\beta-\frac{\alpha}{2}-\delta)\right]\cos[n(\alpha+\delta)] \quad (4)$$

and

$$\delta = \frac{\pi\Delta}{b}; \rho_w = \frac{\pi r_w}{b}; \alpha = \frac{\pi d}{b}; \beta = \frac{1}{2}\frac{\pi e}{b}; \rho = \frac{\pi r}{b}; a = \sqrt{\frac{K_r}{K_z}}$$

Xiang and Kabala (1997) found that the 1993 Solution needed to be modified for large diameter wells to the following:

$$s(r) = \frac{2Q}{\pi K_r b}\sum_{n=1}^{\infty} R_n \frac{K_0(n\rho / a)}{K_1(n\rho_w / a)n\rho_w / a} \quad (5)$$

Table A9 contains data from Dipole Test 7 and results using the various Kabala solutions (1993 and 1997). The large wellbore solution did not differ significantly from the original solution. The average anisotropic ratio at CCAS was approximately 10 but is subject to local aquifer heterogeneities

Kabala's 1993 solution did not match the North Island Data very well and Kabala modified his solution in 2001 to include wellbore storage for unconfined aquifers (Kabala et al.2001):

$$C_{DU} = \frac{1-(r/r_w)^2}{4S} \quad (6)$$

$$C_{DL} = \frac{(r / r_w)^2}{4S} \tag{7}$$

This solution is still under development. Hvilshøj, Jensen and Madsen (2000) found a poor match with the Kabala (1993) method and developed a numerical model for the Vejen test site in Denmark.

5.0 CONCLUSIONS

The hydrogeological investigation of the aquifer treated by the GCW system has yielded meaningful information regarding the hydraulic characteristics of the aquifer and the pumping and injection capacities of the GCW system. The conclusions of the investigation are as follows:

- The calculated aquifer transmissivity ranges from approximately 1,790 to 2,190 square feet per day (ft^2/day) (166 to 203.5 m^2/day) based on analysis using the Hantush-Jacob model. This result is considered higher than the average transmissivity of the deep aquifer zones because of significant recharge (that is, more than normal leakages) from the shallow aquifer zone.

- The hydraulic conductivity of the shallow aquifer zone, calculated using the transmissivities provided previously and based on the estimated saturated aquifer thickness of 42 feet (12.8 m), ranges from 42.9 to 52.5 feet per day (13.1 to 16.0 m). This range of hydraulic conductivity values is typical for clean sand (Freeze and Cherry 1979), which is consistent with the lithology of the shallow aquifer zone at the site.

- The transmissivity of the deep aquifer zone, as calculated from dipole flow test data using the Neuman delayed yield model, ranges from 196 to 337 ft^2/day (18 to 31 m^2/day).

- The hydraulic conductivity of the deep aquifer zone, calculated using the transmissivities provided above and based on an estimated saturated aquifer thickness of 42 feet, ranges from 4.6 to 10.5 feet per day.

- Using the results for the Hantush-Jacob model, the estimated aquifer storativity ranges from 0.03 to 0.07, a typical value range for the average of specific yield and storativity of an unconfined aquifer.

- The specific yield of the aquifer tested ranges from 0.06 to 0.09, based on the Neuman delayed yield model calculation. The storativity values using Neuman's model range from 0.006 to 0.007.

- Using the dipole flow test data, the average anisotropy ratio at CCAS is estimated to be 2.4. The anisotropy ratio is subject to localized aquifer heterogeneities.

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